# Probing nano-engineered quantum vacuum forces


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# Collaborators

## Theory:

Engineering the Casimir force with geometry: Paulo Maia Neto (Rio de Janeiro)
Diego Mazzitelli (Buenos Aires)
Astrid Lambrecht (LKB, Paris)
Serge Reynaud (LKB, Paris)

Engineering the Casimir force with metamaterials: Peter Milonni (LANL)
Felipe da Rosa (LANL)

## Experiments:

BECs for Casimir force: Malcolm Boshier (LANL)

Metamaterials for Casimir force: Antoniette Taylor (CINT, LANL)

Casimir force measurements: Ricardo Decca (Indiana)
Roberto Onofrio (Dartmouth)
Steve Lamoreaux (Yale)

# Outline of this talk

- Brief review of theory and experiments on the Casimir force
- Brief review of theory and experiments on the Casimir-Polder force
- Geometry effects: lateral CP forces with cold atoms
- Materials effects: Casimir repulsion with metamaterials
- Conclusions

# The Casimir force

# The Casimir force

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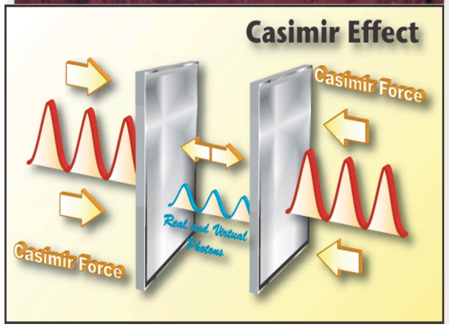


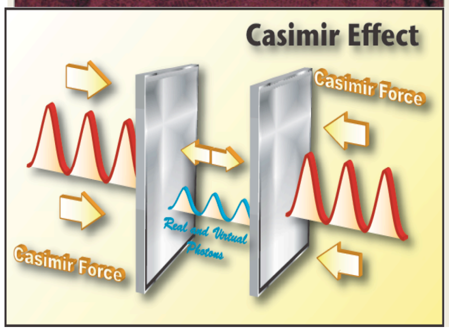

Casimir forces originate from changes in quantum vacuum fluctuations imposed by surface boundaries

They were predicted by the Dutch physicist Hendrik Casimir in 1948

Dominant interaction in the micron and sub-micron lengthscales

$$\boxed{\frac{F}{A} = \frac{\pi^2}{240}\frac{\hbar c}{d^4}} \qquad (130\mathrm{nN/cm^2} \text{ @ } d = 1\mu\mathrm{m})$$

# The Casimir force

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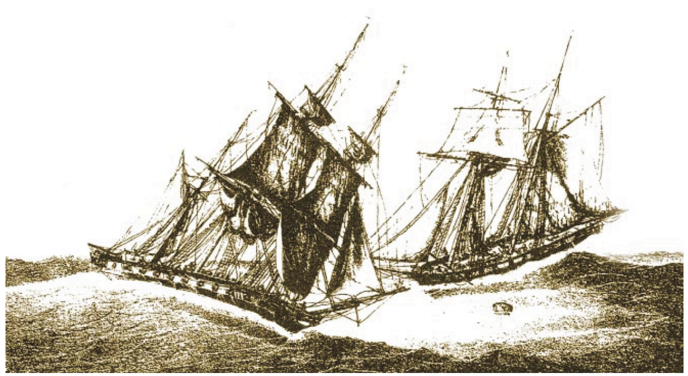
Classical Analog: L'Album du Marin (1836)



# Relevant applications

- ## Gravitation / Particle theory:

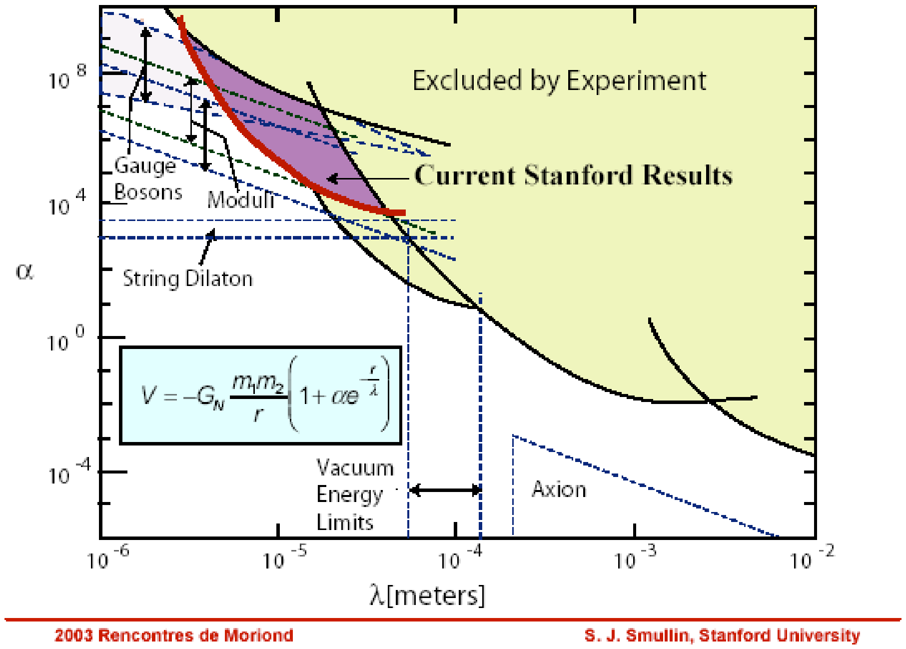
Some theories of particle physics predict deviations from the Newtonian gravitational potentials in the micron and submicron range

The Casimir force is the main background force to measure these non-Newtonian corrections to gravity

Yukawa-like potential:

$$V(r) = -G\frac{m_1 m_2}{r}\left(1 + \alpha\, e^{-r/\lambda}\right)$$

**Phase Space**



# Relevant applications

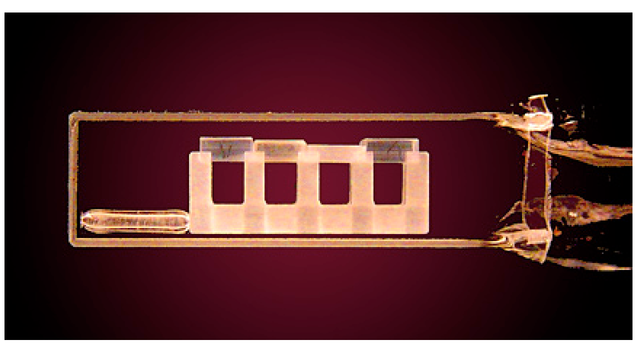
## Quantum Science and Technology:

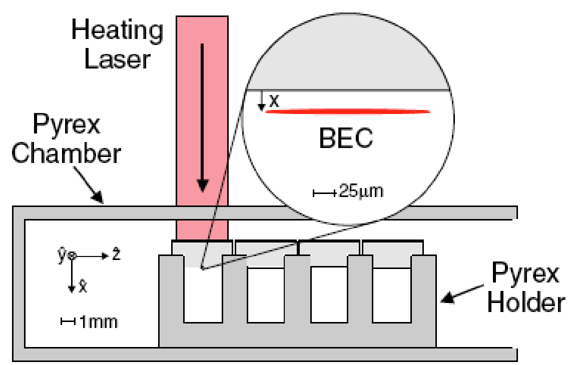
Atom-surface interactions

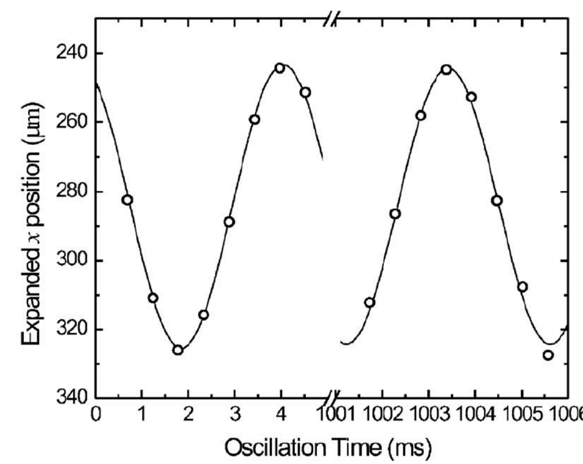
Precision measurements

Example: Casimir-Polder interaction between a BEC and a surface

Cornell et al (2007)





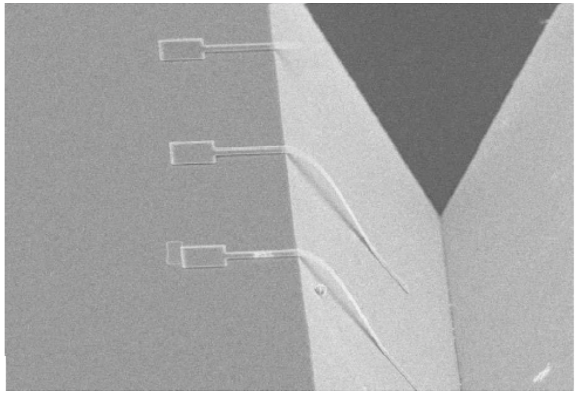

$$\gamma_x \equiv \frac{\omega_x - \omega_x'}{\omega_x} \simeq -\frac{1}{2\omega_x^2 m}\partial_x^2 U^*$$

# Relevant applications

- Nanotechnology:

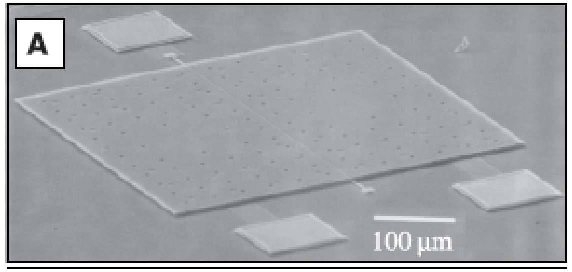
Problems with stiction of movable parts in MEMS

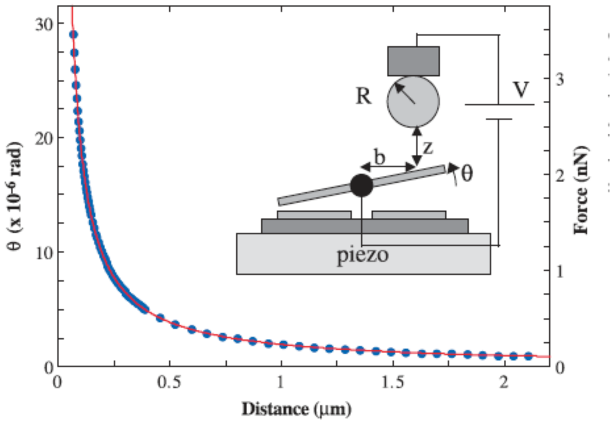
“pull-in” effect



Zhao et al (2003)

Actuation in NEMS and MEMS driven by Casimir forces

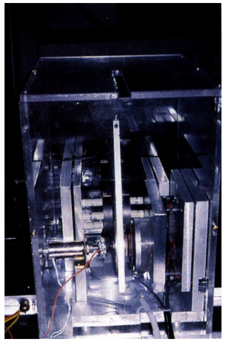
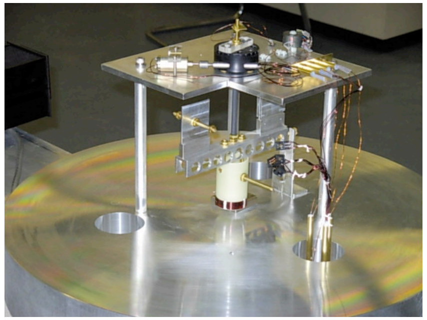



Capasso et al (2001)

# Modern Casimir experiments

## Torsion pendulum

sphere-plane, d=1-10 um
Lamoreaux

# Modern Casimir experiments

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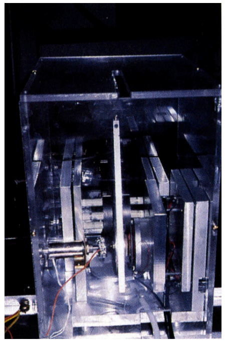

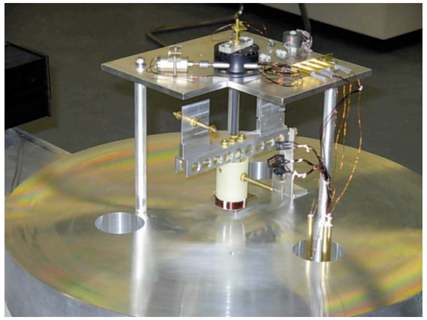

sphere-plane, d=1-10 um
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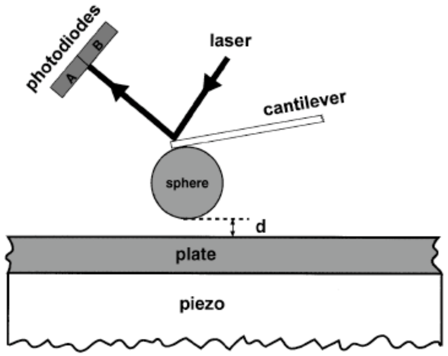
- Atomic force microscope




sphere-plane, d=200-1000 nm
Mohideen et al

# Modern Casimir experiments

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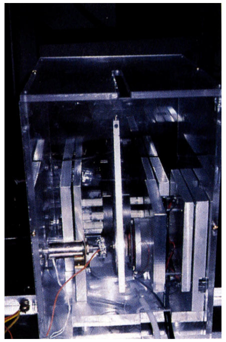

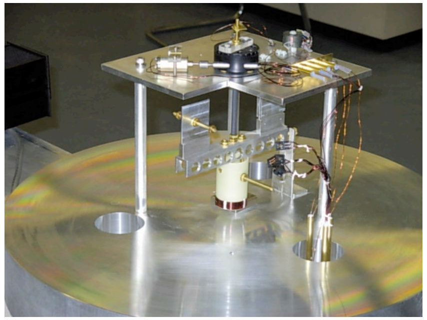

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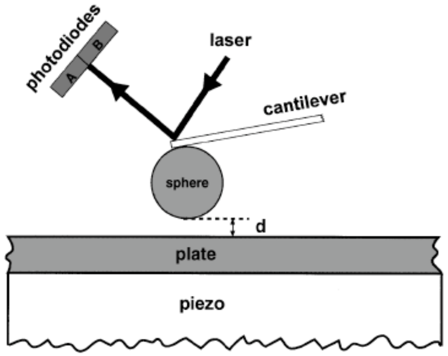
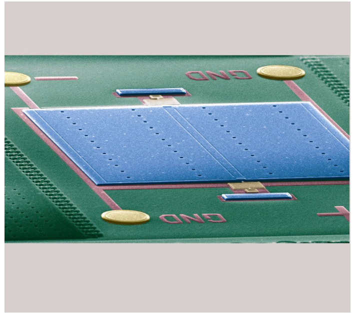



sphere-plane, d=200-1000 nm
Mohideen et al

- MEMS and NEMS



sphere-plane, d=200-1000 nm
Capasso et al, Decca et al

# Modern Casimir experiments

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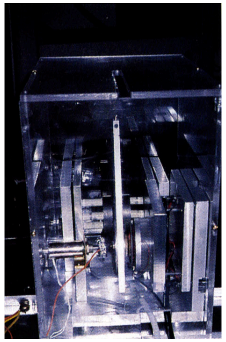

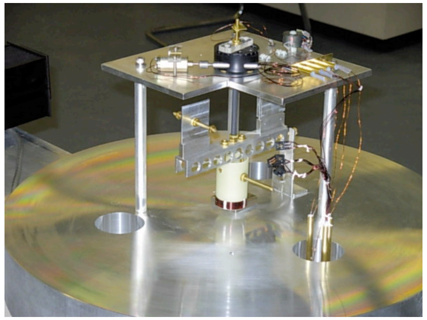

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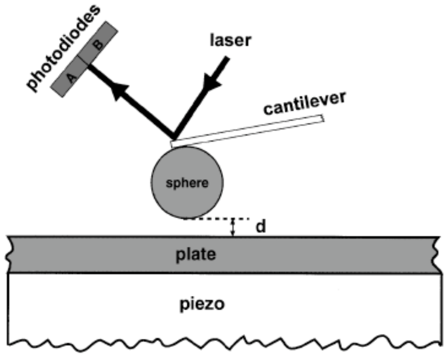


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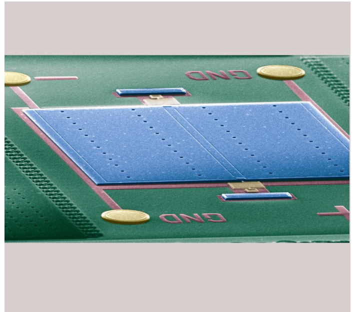


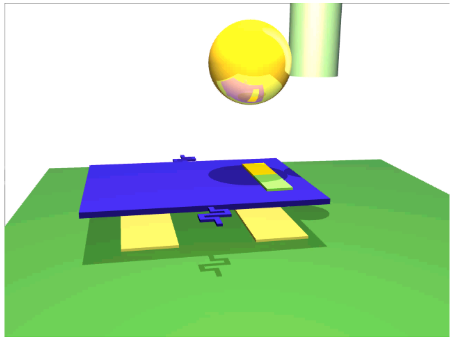

sphere-plane, d=200-1000 nm
Capasso et al, Decca et al

# Modern Casimir experiments

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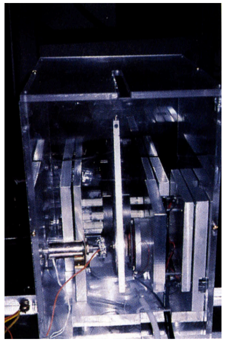
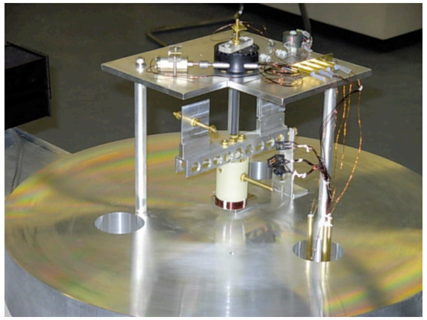

sphere-plane, d=1-10 um
Lamoreaux

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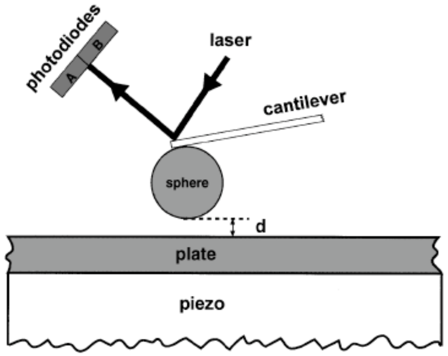


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Mohideen et al

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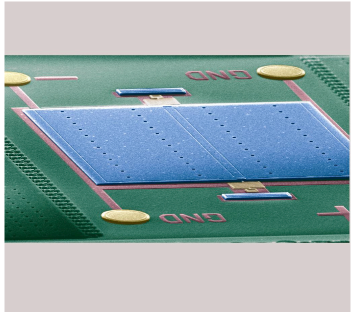
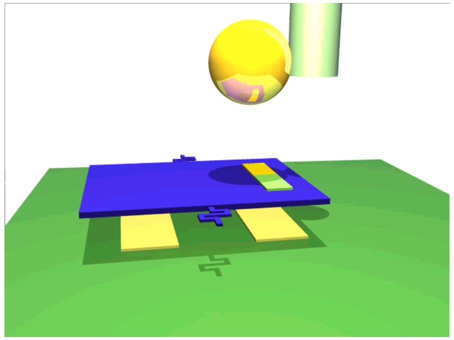
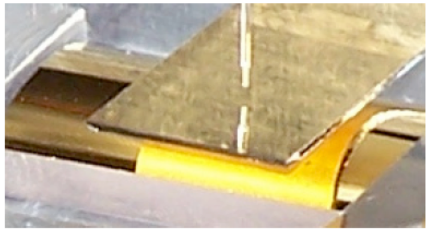




sphere-plane, d=200-1000 nm
Capasso et al, Decca et al

## Micro-cantilever



plane-plane, cylinder-plane, d=1-3 um
Onofrio et al

# Tailoring the Casimir force

- The magnitude and sign of the Casimir force depend on the geometry and composition of surfaces

Engineer geometries and designer materials for various applications:

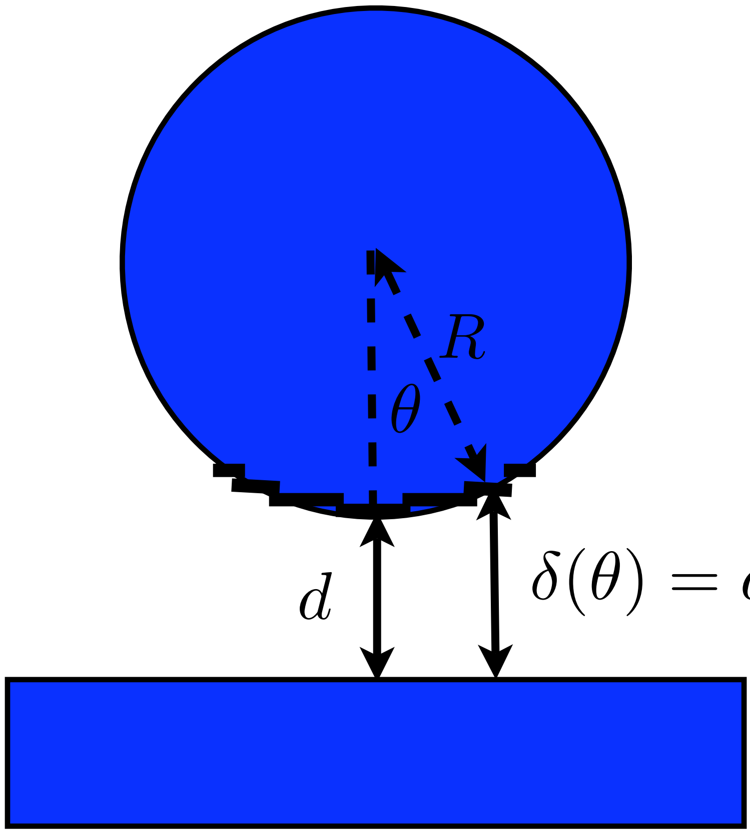
- Demonstration of strongly modified/repulsive Casimir forces
- Demonstration of vacuum drag via lateral Casimir forces

- Effects of geometry: proximity force approx and beyond

- Effects of materials: Lifshitz formula and beyond

# Geometry effects: PFA

- The Proximity Force Approximation (PFA) corresponds to approximating the Casimir energy by its expression for the planar case, averaging over local planes




$$E_{\rm SP}^{\rm PFA}(d) \approx 2\pi R^2 \int_0^{\theta_m} d\theta \sin\theta \, \frac{E_{\rm PP}(\delta(\theta))}{A}$$

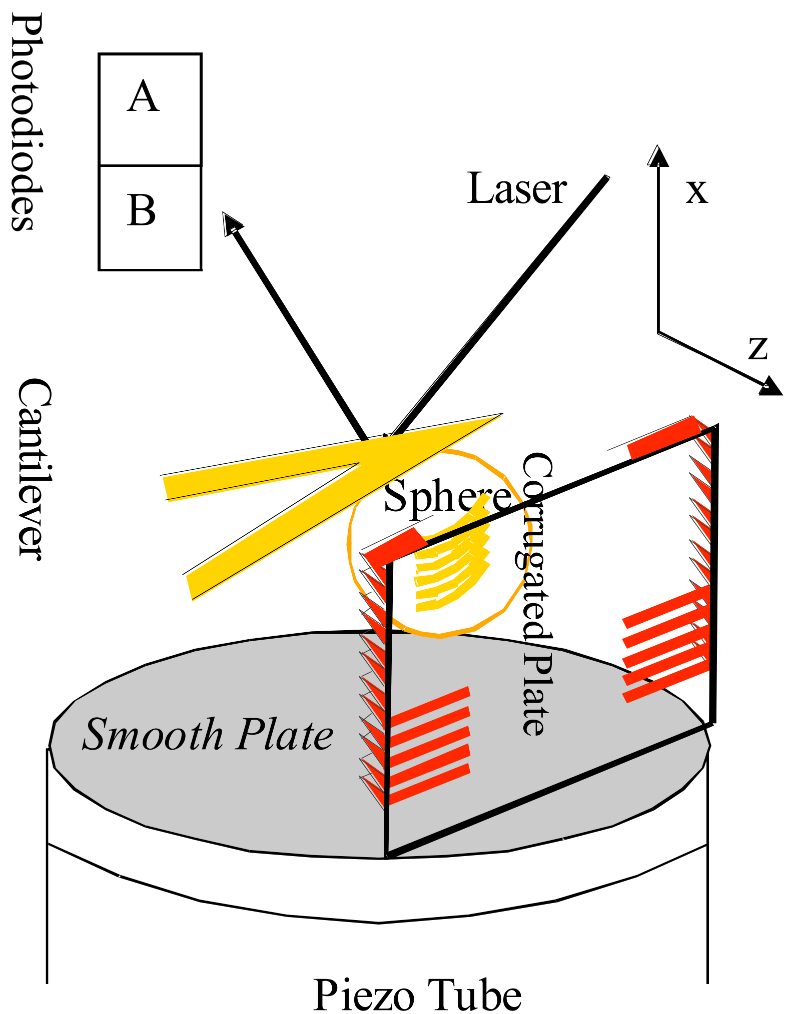
It is a good approximation when $R \gg d$

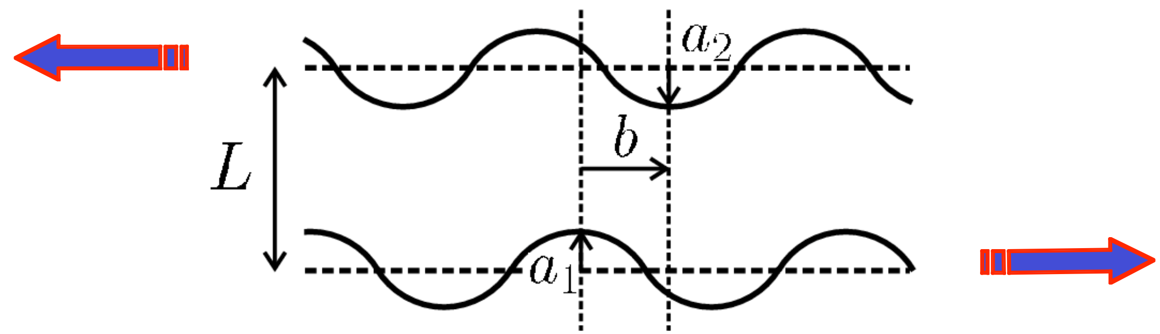
$$\delta(\theta) = d + R\,(1 - \cos\theta)$$

- There are a few perturbative methods to go beyond PFA, and also exact results for a few geometries with perfectly conducting surfaces (cylinder-plane, eccentric cylinders, etc).

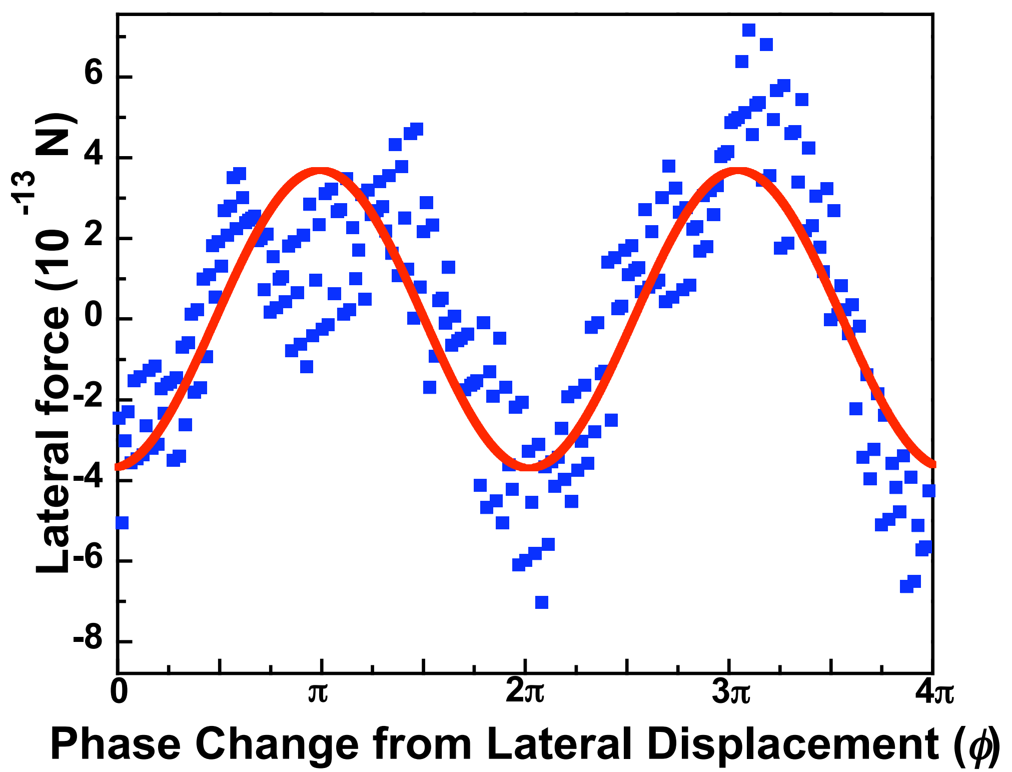
# Geometry effects: lateral force

Mohideen et al (2002)




$L = 200 - 500$ nm $\quad a_{1,2} \approx 50$ nm



# Materials effects: Lifshitz eqn.

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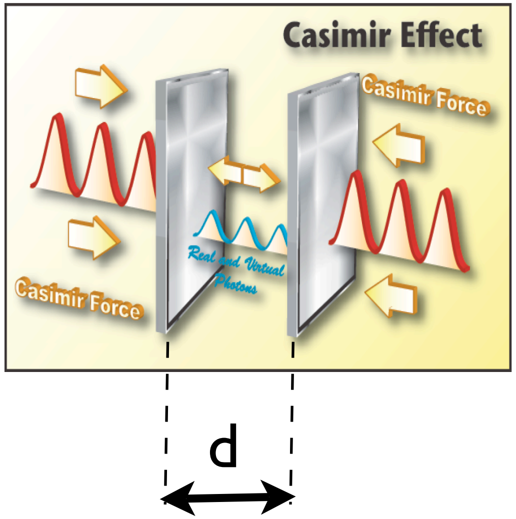
The Lifshitz formula: Lifshitz (1956)

$$\frac{F}{A} = 2k_B T \sum_{n=0}^{\infty} \int_{\xi_n/c}^{\infty} \frac{d\kappa}{2\pi} \kappa^2 \sum_{\lambda=\mathrm{TE},\mathrm{TM}} \left( \frac{e^{2\kappa d}}{r_{\lambda_1} r_{\lambda_2}} - 1 \right)^{-1}$$




$$\omega_n = i\xi_n = 2\pi i n k_B T/\hbar$$ Matsubara frequencies

Reflection coefficients

$$r_{\mathrm{TM}} = \frac{\epsilon(i\xi_n)c\kappa - \sqrt{\xi_n^2[\epsilon(i\xi_n)\mu(i\xi_n) - 1] + \kappa^2 c^2}}{\epsilon(i\xi_n)c\kappa + \sqrt{\xi_n^2[\epsilon(i\xi_n)\mu(i\xi_n) - 1] + \kappa^2 c^2}}$$

$$r_{\mathrm{TE}} = r_{\mathrm{TM}} \text{ with } \epsilon \leftrightarrow \mu$$

Dominant frequencies in the near-infrared/optical region of the EM spectrum (gaps d= 200-1000 nm)

Kramers-Kronig (causality) relations:

$$\epsilon(i\xi_n) = 1 + \frac{2}{\pi} \int_0^{\infty} \frac{\omega \epsilon''(\omega)}{\omega^2 + \xi_n^2} d\omega \qquad \mu(i\xi_n) = 1 + \frac{2}{\pi} \int_0^{\infty} \frac{\omega \mu''(\omega)}{\omega^2 + \xi_n^2} d\omega$$

# The Casimir-Polder force

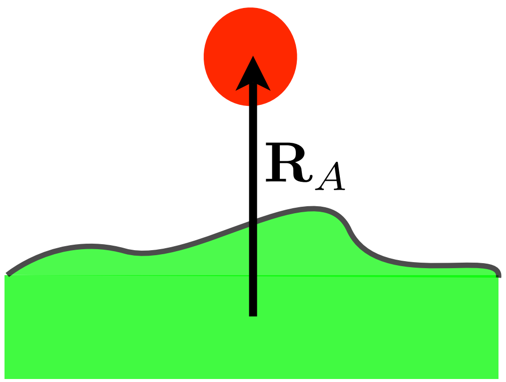
# The Casimir-Polder force

## vdW - CP interaction

Casimir and Polder (1948)

The interaction energy between a ground-state atom and a surface is given by

$$\boxed{U_{\mathrm{CP}}(\mathbf{R}_A) = \frac{\hbar}{c^2\epsilon_0}\int_0^\infty \frac{d\xi}{2\pi}\xi^2\alpha(i\xi)\,\mathrm{Tr}\,\mathbf{G}(\mathbf{R}_A,\mathbf{R}_A,i\xi)}$$




Atomic polarizability: $\alpha(\omega) = \lim_{\epsilon\to 0}\frac{2}{3\hbar}\sum_k \frac{\omega_{k0}|\mathbf{d}_{0k}|^2}{\omega_{k0}^2-\omega^2-i\omega\epsilon}$

Scattering Green tensor: $\left(\nabla\times\nabla\times-\frac{\omega^2}{c^2}\epsilon(\mathbf{r},\omega)\right)\mathbf{G}(\mathbf{r},\mathbf{r}',\omega) = \delta(\mathbf{r}-\mathbf{r}')$

# The Casimir-Polder force

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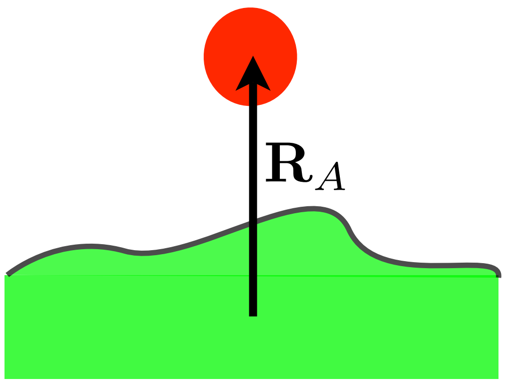


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- ## Eg: Ground-state atom near planar surface @ T=0

Non-retarded (vdW) limit $z_A \ll \lambda_A$

$$U_{\rm vdW}(z_A) = -\frac{\hbar}{8\pi\epsilon_0}\frac{1}{z_A^3}\int_0^\infty\frac{d\xi}{2\pi}\alpha(i\xi)\frac{\epsilon(i\xi)-1}{\epsilon(i\xi)+1}$$

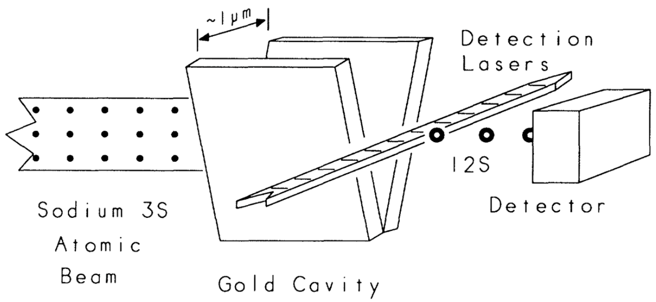
Retarded (CP) limit $z_A \gg \lambda_A$

$$U_{\rm CP}(z_A) = -\frac{3\hbar c\alpha(0)}{8\pi}\frac{1}{z_A^4}\frac{\epsilon_0-1}{\epsilon_0+1}\phi(\epsilon_0)$$

# Modern CP experiments

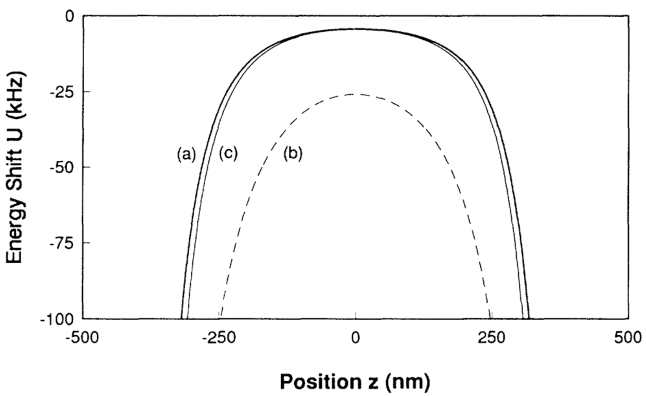
- Deflection of atoms

Hinds et al (1993)




L= 0.7-1.2 um

Exp-Th agreement @ 10%



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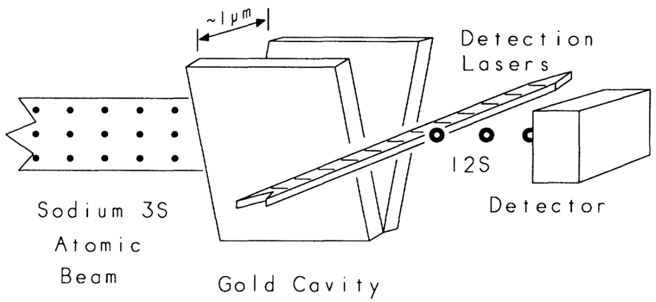


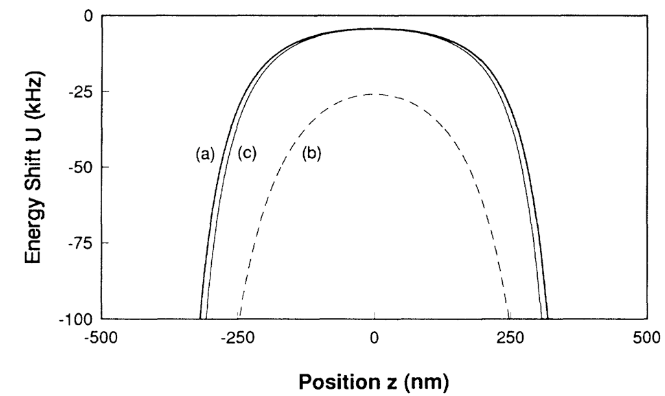


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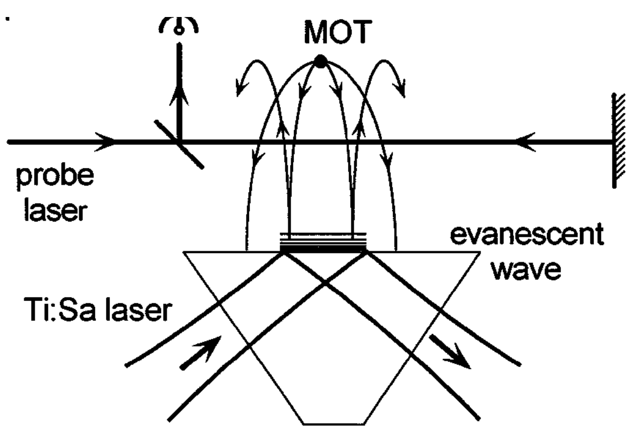
Exp-Th agreement @ 10%

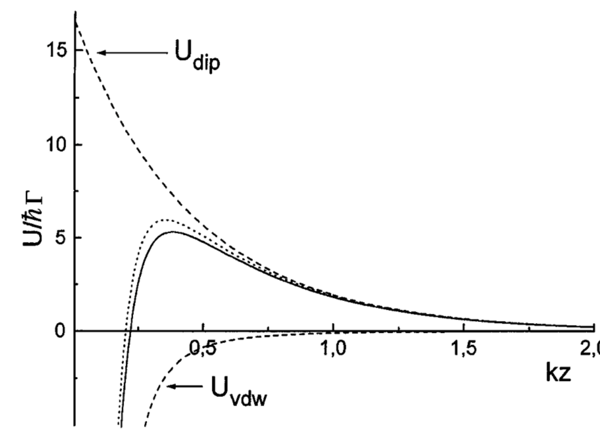
## Classical reflection on atomic mirror

Aspect et al (1996)




$$U_{\rm dip} = \frac{\hbar}{4}\frac{\Omega^2}{\Delta}\, e^{-2kz}$$

$$U_{\rm vdW} = -\frac{\epsilon-1}{\epsilon+1}\frac{1}{48\pi\epsilon_0}\frac{D^2}{z^3}$$

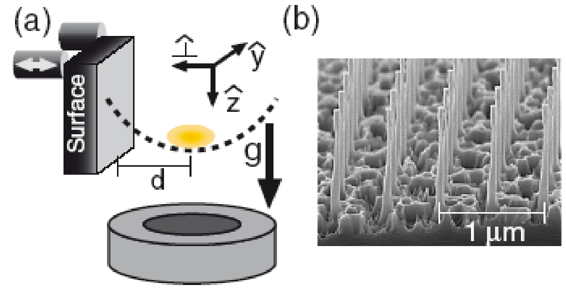


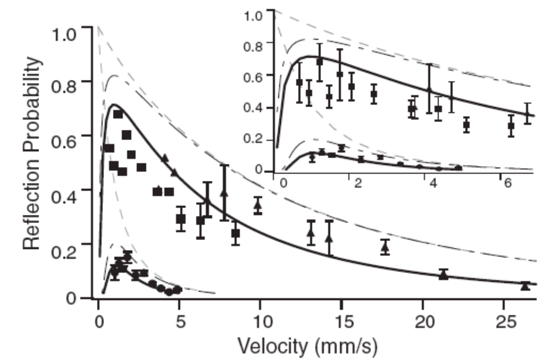

Exp-Th agreement @ 30%

# Modern experiments (cont'd)

## Quantum reflection

Wave-nature of atoms implies that slow atoms can reflect from purely attractive potentials




$$k = \sqrt{k_0^2 - 2mU/\hbar^2} \qquad \phi = \frac{1}{k^2}\frac{dk}{dr} > 1$$

$$U = -C_n/r^n \ (n > 2)$$

Shimizu (2001) Ketterle et al (2006)

DeKievet et al (2003)

# Modern experiments (cont'd)

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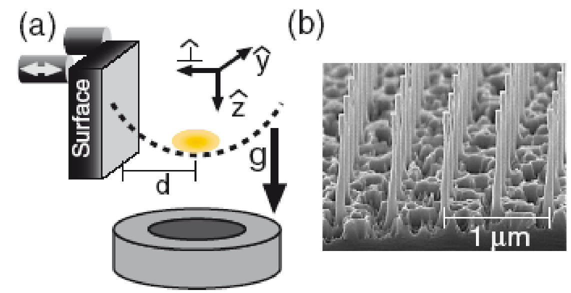


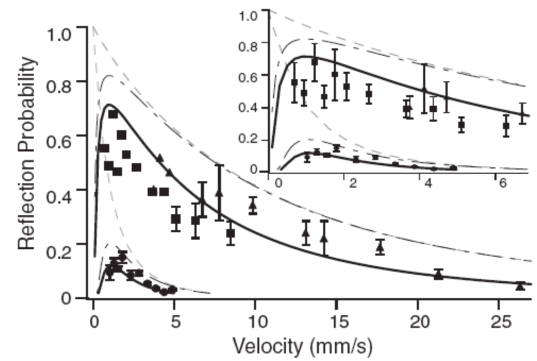


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Shimizu (2001)    Ketterle et al (2006)

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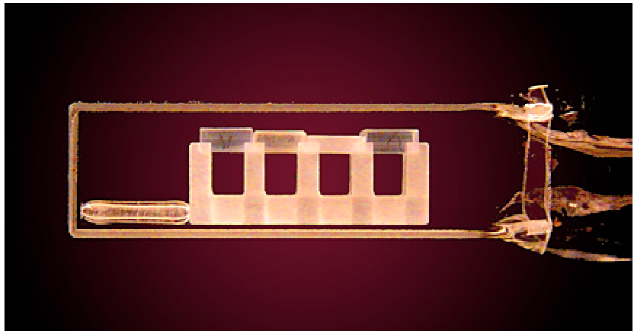
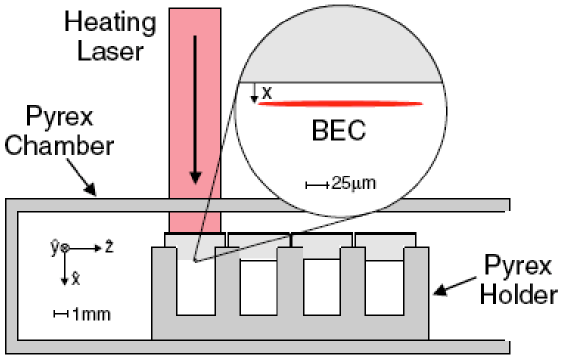
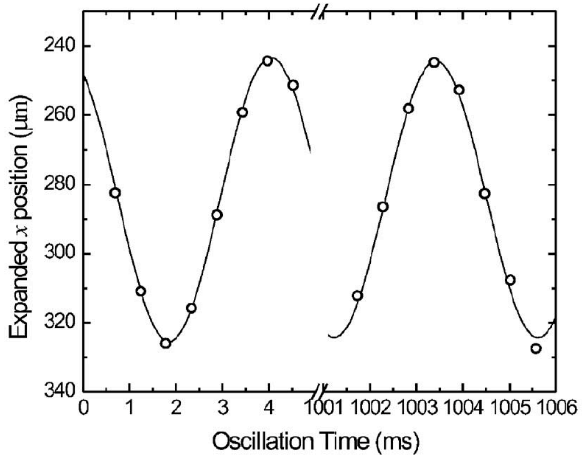
## BEC oscillator

Cornell et al (2007)

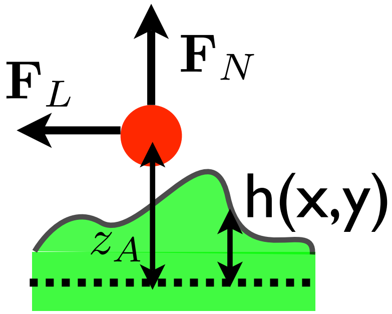





$$\gamma_x \equiv \frac{\omega_x - \omega_x'}{\omega_x} \simeq -\frac{1}{2\omega_x^2 m}\partial_x^2 U^*$$

# Lateral Casimir-Polder force




$$U_{\rm CP} = U^{(0)}_{\rm CP}(z_A) + U^{(1)}_{\rm CP}(z_A, x_A)$$

- Normal CP force: $$U^{(0)}_{\rm CP}(z_A) = \frac{\hbar}{c^2\epsilon_0}\int_0^\infty \frac{d\xi}{2\pi}\xi^2\alpha(i\xi)\int\frac{d^2\mathbf{k}}{(2\pi)^2}\frac{1}{2\kappa}\sum_p \hat{\epsilon}_p^+\cdot\hat{\epsilon}_p^-\ r_p(\mathbf{k},\xi)\ e^{-2\kappa z_A}$$

- Lateral CP force: $$\boxed{U^{(1)}_{\rm CP}(z_A, x_A) = \int\frac{d^2\mathbf{k}}{(2\pi)^2}\ e^{i\mathbf{k}\cdot\mathbf{r}_A}\ g(\mathbf{k}, z_A)\ H(\mathbf{k})}$$

Response function g:

$$g(\mathbf{k}, z_A) = \frac{\hbar}{c^2\epsilon_0}\int_0^\infty \frac{d\xi}{2\pi}\xi^2\alpha(i\xi)\int\frac{d^2\mathbf{k}'}{(2\pi)^2}\ a_{\mathbf{k}',\mathbf{k}'-\mathbf{k}}(z_A,\xi)$$

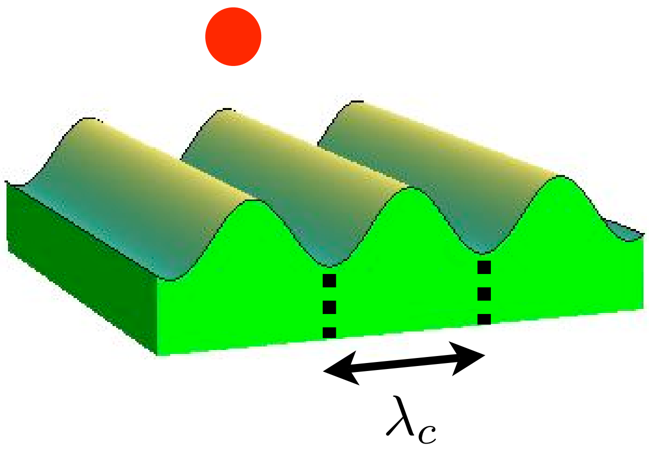
$$a_{\mathbf{k}',\mathbf{k}''} = \sum_{p',p''}\hat{\epsilon}_{p'}^+\cdot\hat{\epsilon}_{p''}^-\ \frac{e^{-(\kappa'+\kappa'')z_A}}{2\kappa''}\ R_{p',p''}(\mathbf{k}',\mathbf{k}'')$$

The non-specular reflection matrices depend on the geometry and material properties.

# Corrugated surfaces

Uni-axial corrugation: $h(x, y) = h_0 \cos(k_c\, x)$

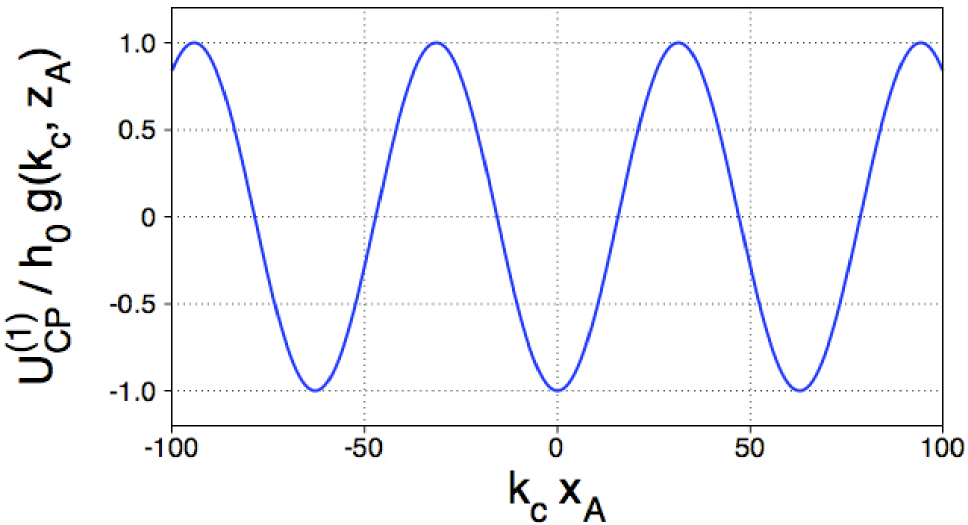
Corrugation period: $\lambda_c = 2\pi / k_c$




## Lateral Casimir-Polder force:

$$U_{\rm CP}^{(1)} = h_0 \cos(k_c\, x_A)\; g(k_c, z_A)$$

$$\mathbf{F}_L = k_c h_0 \sin(k_c\; x_A)\; g(k_c, z_A)\; \mathbf{x}$$

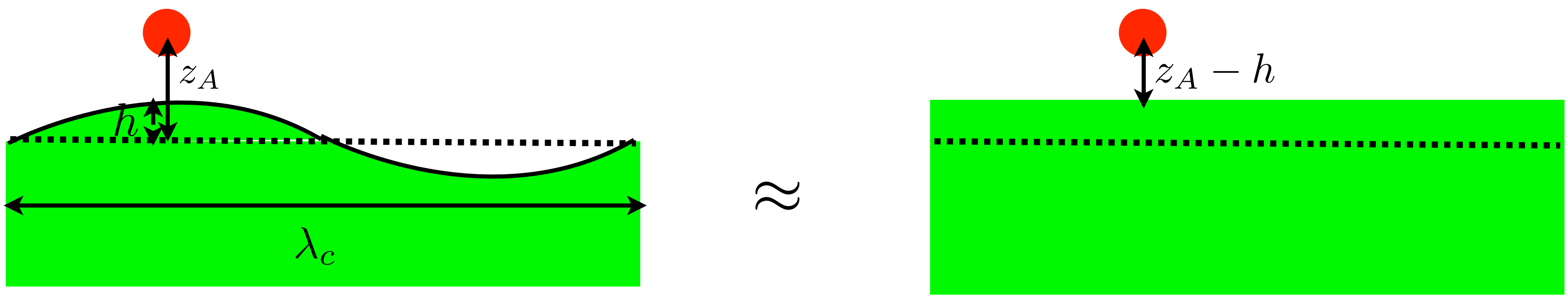



We will show below that $g(k_c, z_A) < 0$ , so that the lateral force brings the atom to the neighborhood of one of the crests

# PFA in Casimir-Polder forces

- The PFA corresponds to approximating the CP energy by its expression for the planar case with a "local" distance $z_A - h(\mathbf{r}_A)$

$$U_{\mathrm{CP}}(\mathbf{R}_A) \approx U^{(0)}_{\mathrm{CP}}(z_A - h(\mathbf{r}_A)) \approx U^{(0)}_{\mathrm{CP}}(z_A) - h(\mathbf{r}_A)\, U^{(0)\prime}_{\mathrm{CP}}(z_A)$$




- The PFA corresponds to the limiting case where the corrugation is very smooth with respect to the other length scales.

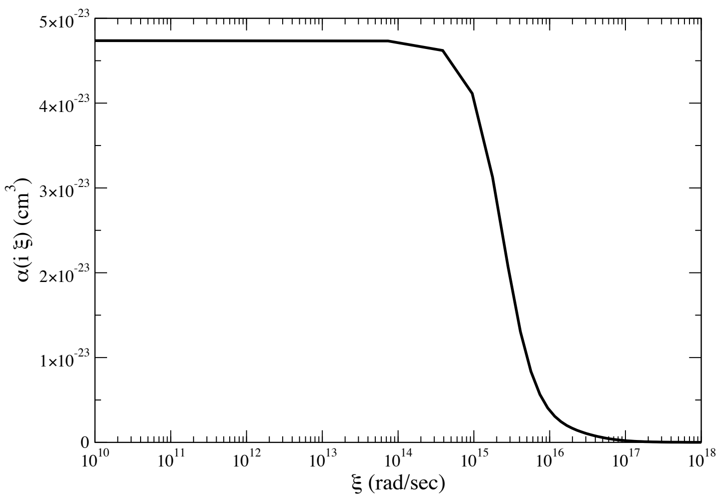
$$\boxed{k_c\, z_A \ll 1 \qquad \text{[PFA]}}$$

- Deviations from PFA can be measured by the ratio

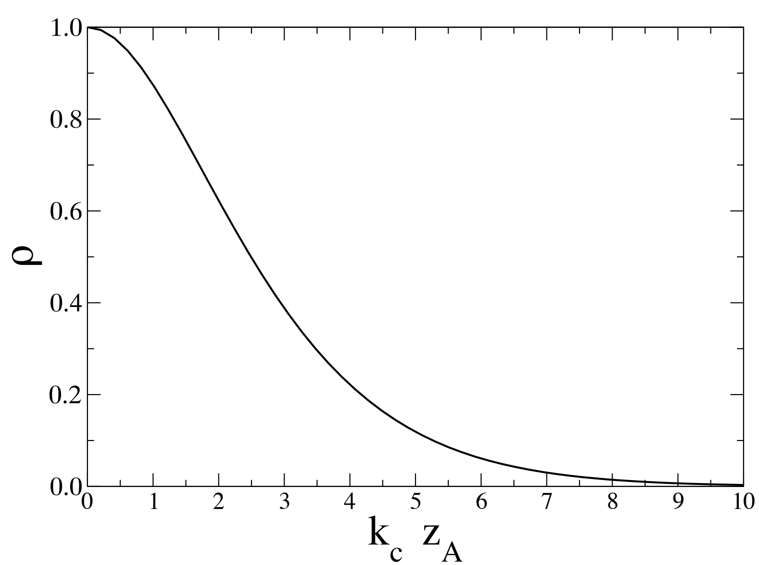
$$\boxed{\rho \equiv \frac{g(k_c, z_A)}{g(0, z_A)}}$$

# Non-trivial geometry effects

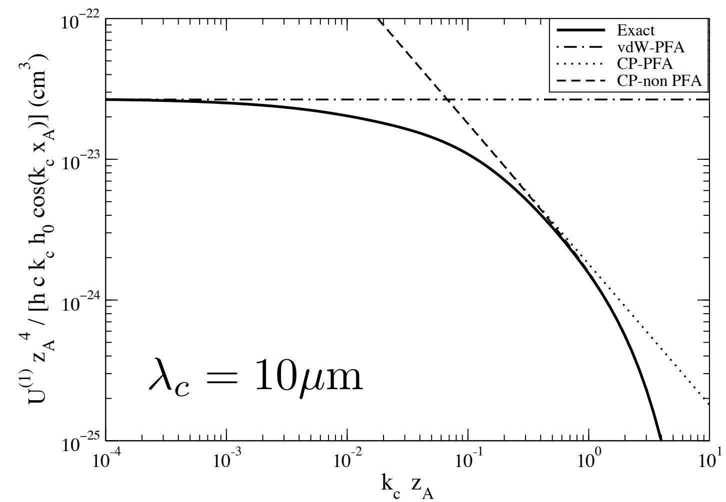
- Dynamic polarizability of Rb
  Babb et al (1999)




- Deviations from PFA




- Lateral potential energy $U^{(1)}$
  Rb + sine corrug. + perf. reflector



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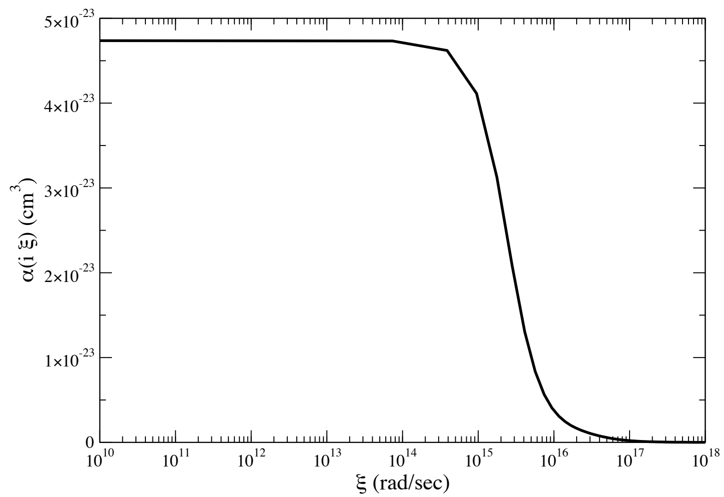


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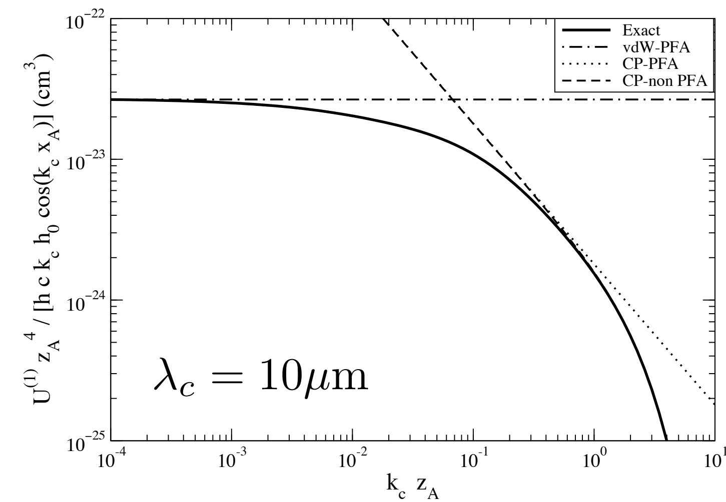


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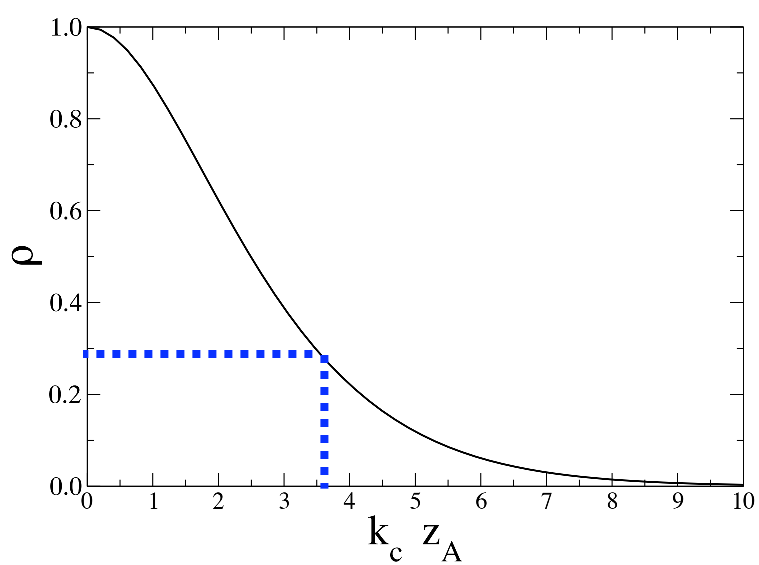



**Example:**

atom-surface distance $z_A = 2\mu\mathrm{m} \gg \lambda_A$

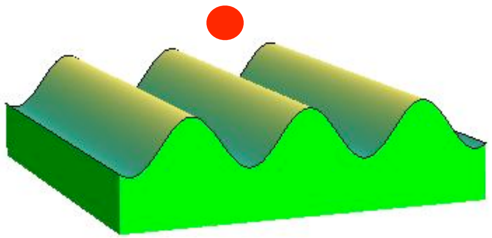
corrugation wavelength $\lambda_c = 3.5\mu\mathrm{m}$

$\rho \approx 30\%$

PFA largely overestimates the magnitude of the lateral effect !

# Atoms as local probes

- Before we described large deviations from PFA for a sinusoidal corrugated surface.



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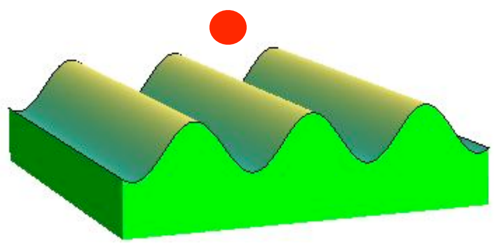
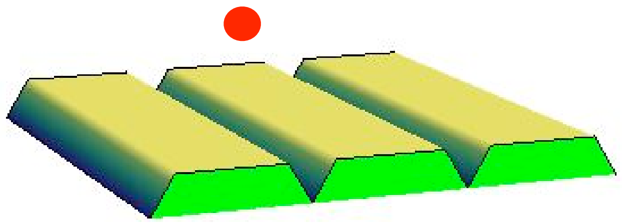


- Even larger deviations from PFA can be obtained for a periodically grooved surface.



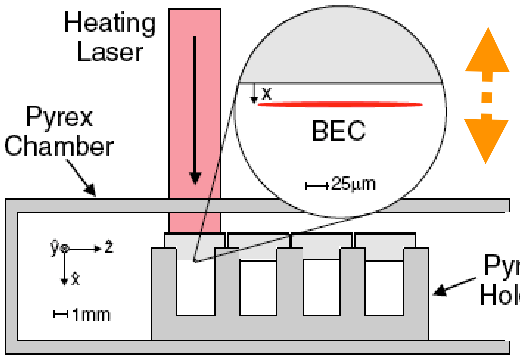
- If the atom is located above one plateau, the PFA predicts that the lateral Casimir-Polder force should vanish, since the energy is thus unchanged in a small lateral displacement.

- A non-vanishing force appearing when the atom is moved above the plateau thus clearly signals a deviation from PFA!

# BEC as a vacuum field sensor

## BEC oscillator

- Normal Casimir-Polder force $U^{(0)}_{\rm CP}(z)$ shifts the normal dipolar oscillation frequency of a BEC trapped above a surface




Cornell et al (2005, 2007)

# BEC as a vacuum field sensor

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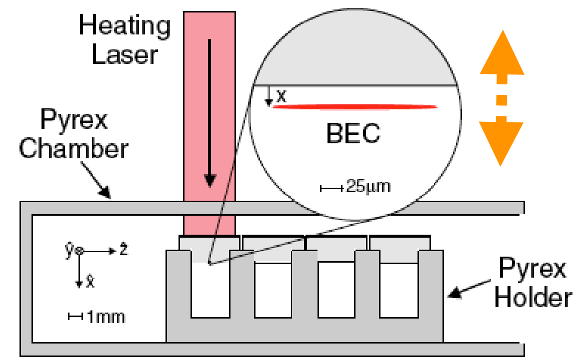
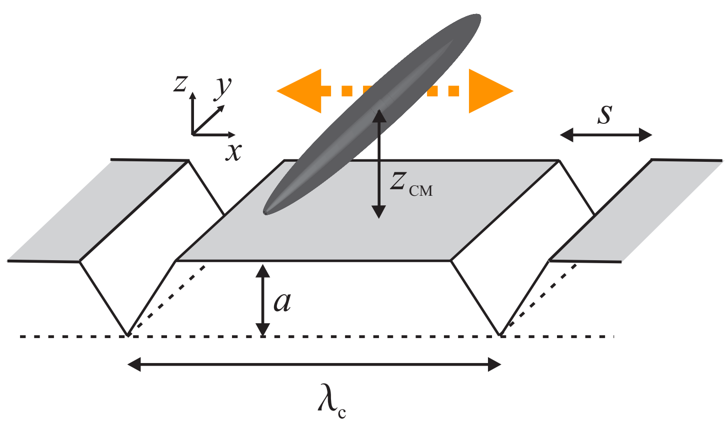



Cornell et al (2005, 2007)

- Lateral Casimir-Polder force $U_{\mathrm{CP}}^{(1)}(x,z)$ shifts the lateral dipolar oscillation frequency of a BEC trapped above a grooved surface



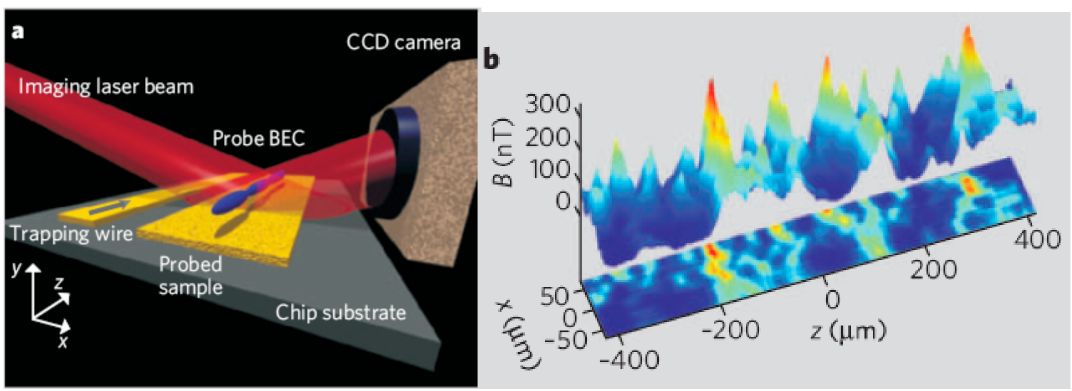

Lateral frequency shift:

$$\omega_{x,\mathrm{CM}}^2 = \omega_x^2 + \frac{1}{m}\int dx dz\, n_0(x,z) \frac{\partial^2}{\partial x^2} U_{\mathrm{CP}}^{(1)}(x,z)$$

# BEC as a vacuum field sensor

## Density variations of a BEC above an atom chip

- For a quasi one-dimensional BEC, the potential is related to the 1D density profile as: $V_{\rm ho}(x) + U_{\rm CP}(x) = -\hbar\omega_x\sqrt{1+4a_{\rm scat}n_{1d}(x)}$




Schmiedmayer et al (2005)

Measurement of the magnetic field variations along a current-carrying wire

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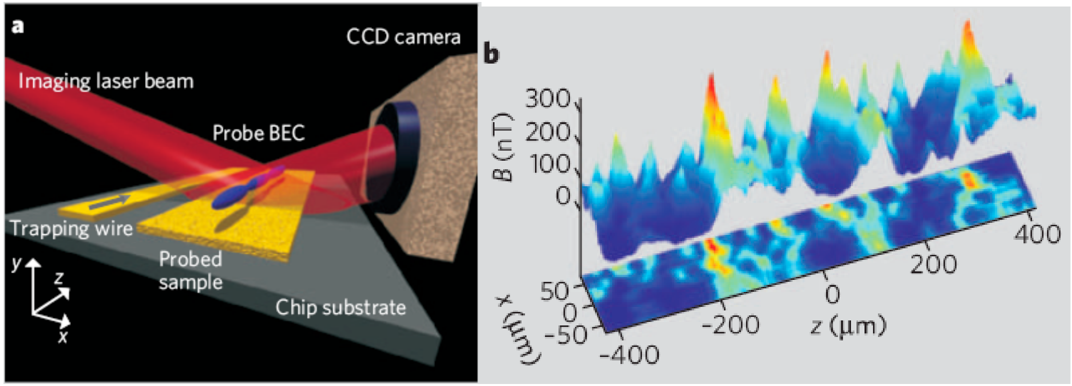
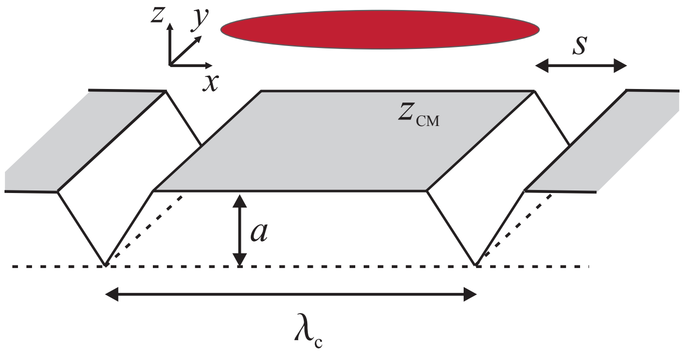


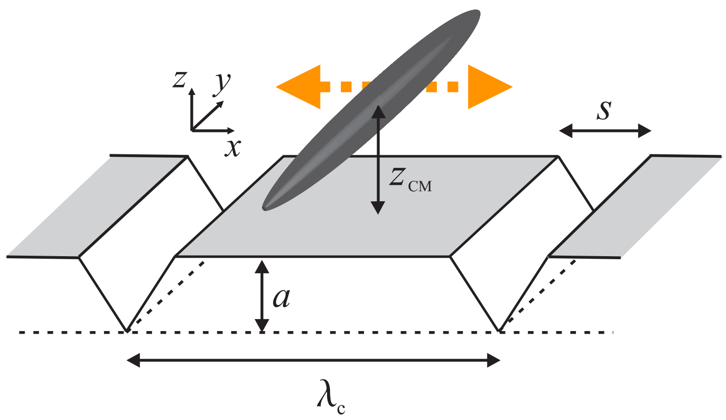

Schmiedmayer et al (2005)

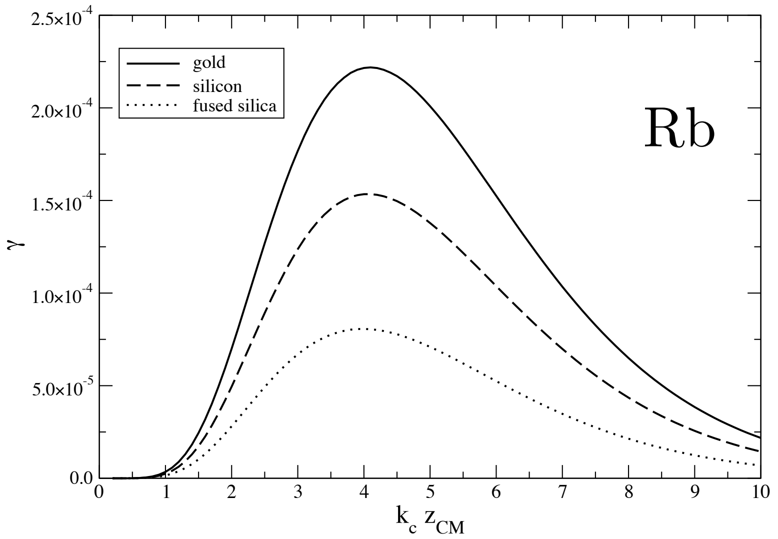
Measurement of the magnetic field variations along a current-carrying wire

- Density modulation along the BEC above the plateau would be a signature of lateral Casimir-Polder forces



# Frequency shift for BEC (cont'd)




- Relative frequency shift

$$\boxed{\gamma_0 \equiv \frac{\omega_{x,\mathrm{CM}} - \omega_x}{\omega_x}}$$

$$z_{\mathrm{CM}} = 2\mu\mathrm{m} \qquad \omega_x/2\pi = 229\,\mathrm{Hz}$$

$$s = \lambda_c/2 \qquad a = 250\mathrm{nm}$$

# Frequency shift for BEC (cont'd)

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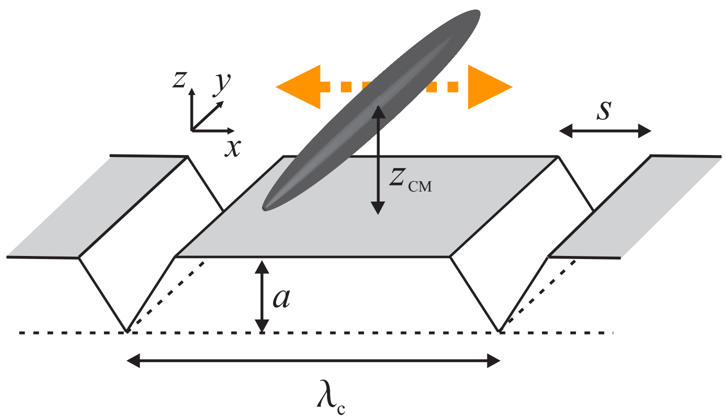


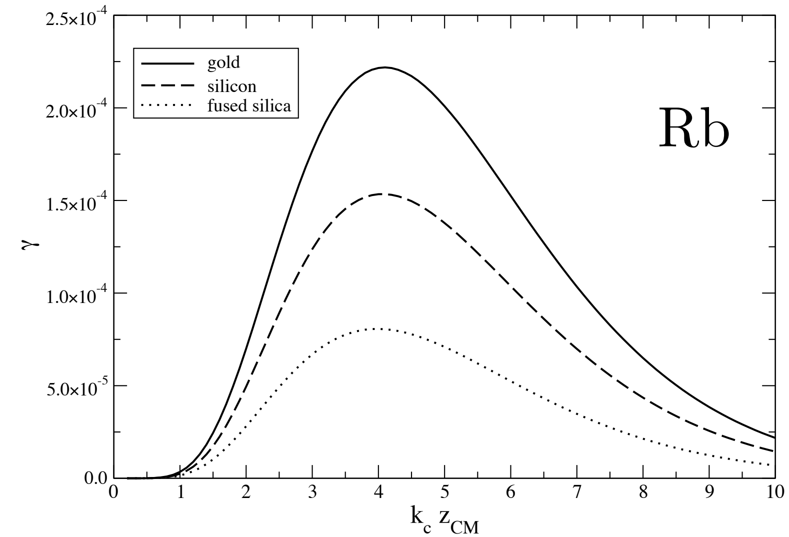


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$$s = \lambda_c/2 \qquad a = 250\mathrm{nm}$$

Given the reported sensitivity $\gamma = 10^{-5} - 10^{-4}$ for relative frequency shifts from E. Cornell's experiment, we expect that beyond-PFA lateral CP forces on a BEC above a plateau of a periodically grooved silicon surface should be detectable for distances $z_{\mathrm{CM}} < 3\mu\mathrm{m}$, groove period $\lambda_c = 4\mu\mathrm{m}$, groove amplitude $a = 250\mathrm{nm}$, and a BEC radius of, say, $R \approx 1\mu\mathrm{m}$

# Summary I

- Novel cold atoms techniques open a promising way of investigating nontrivial geometrical effects on quantum vacuum
- Important feature of atoms: they can be used as <u>local</u> probes of quantum vacuum fluctuations
- We predict <u>large deviations from PFA</u> for the lateral Casimir-Polder force on an atom above a corrugated surface
- Non-trivial, beyond-PFA effects should be measurable using a BEC as a vacuum field sensor with available technology

For more details see: Dalvit, Maia Neto, Lambrecht, and Reynaud, arXiv:0709.2095, 0710.5249

# Metamaterials and Casimir

# Metamaterials and Casimir

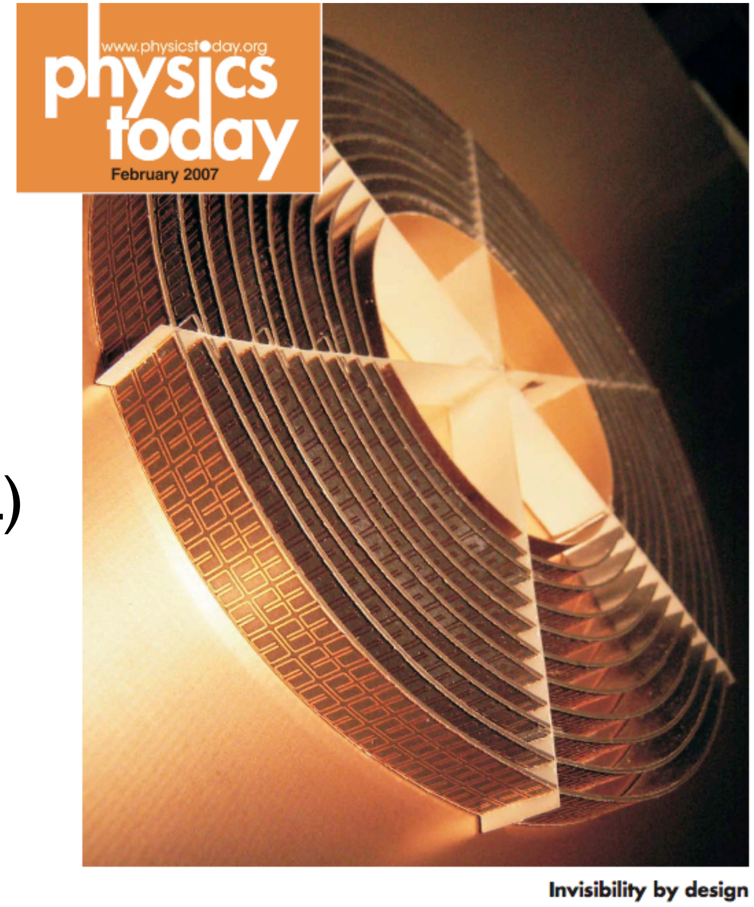
- Artificial materials for engineering the Casimir force

Ongoing work in collaboration with:

Theory: Peter Milonni (LANL)

Felipe da Rosa (LANL)

Experiment: Antoniette Taylor (CINT, LANL)



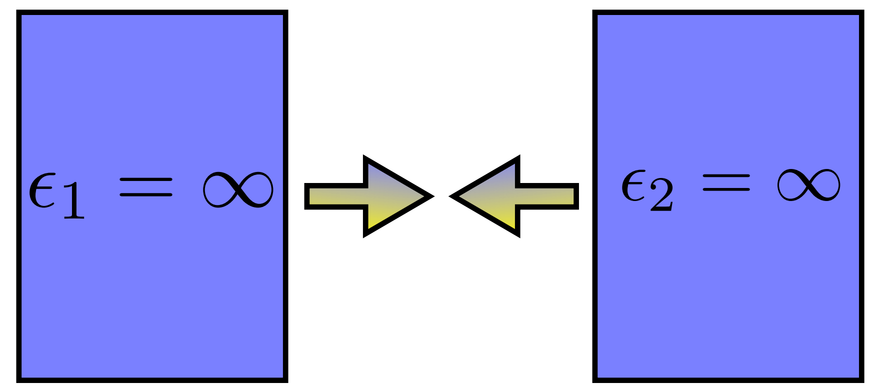

Smith et al (2007)

# Casimir attraction-repulsion

- Ideal attractive limit

Casimir 1948

$$\boxed{\frac{F}{A} = +\frac{\pi^2}{240}\,\frac{\hbar c}{d^4}}$$



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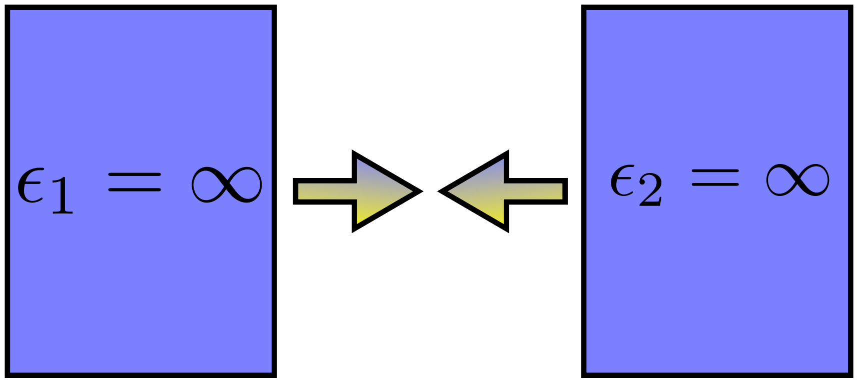


- Ideal repulsive limit

Boyer 1974

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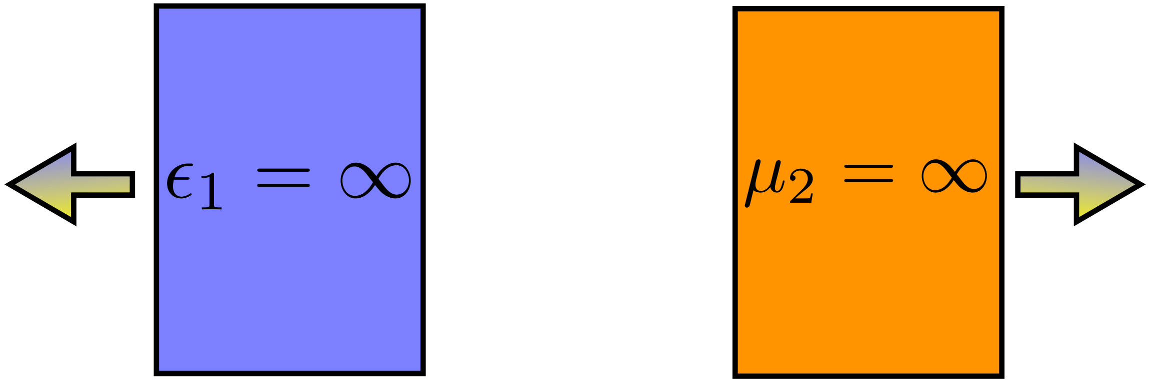

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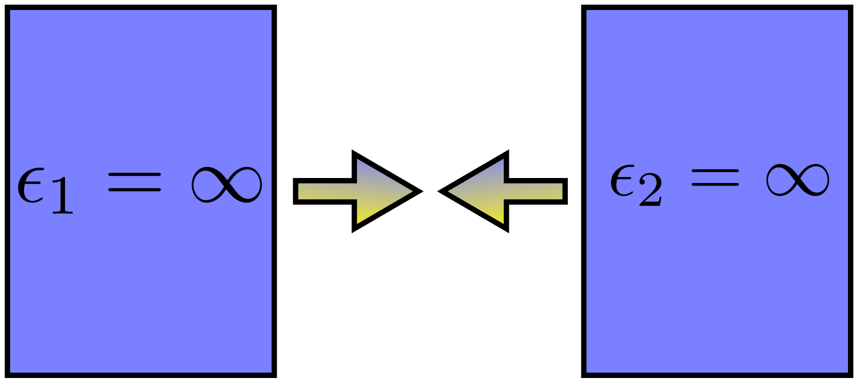


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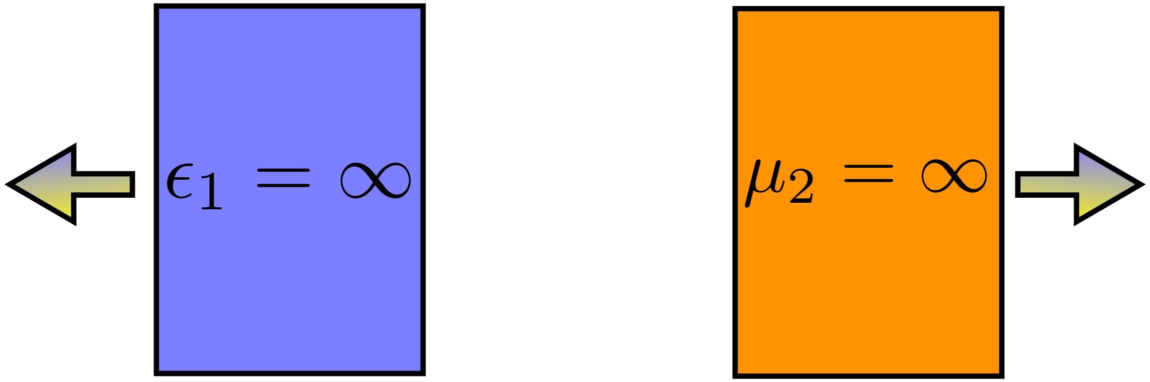


- ## Real repulsive limit

Casimir repulsion is associated with strong electric-magnetic interactions. However, natural occurring materials do NOT have strong magnetic response in the optical region, i.e. $\mu = 1$

# Casimir attraction-repulsion

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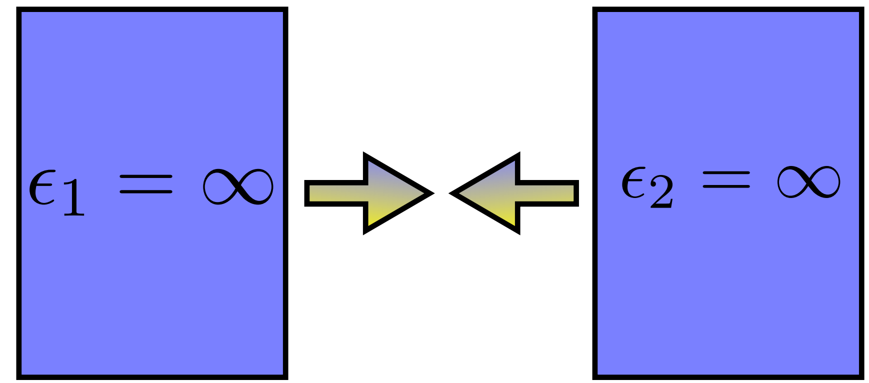


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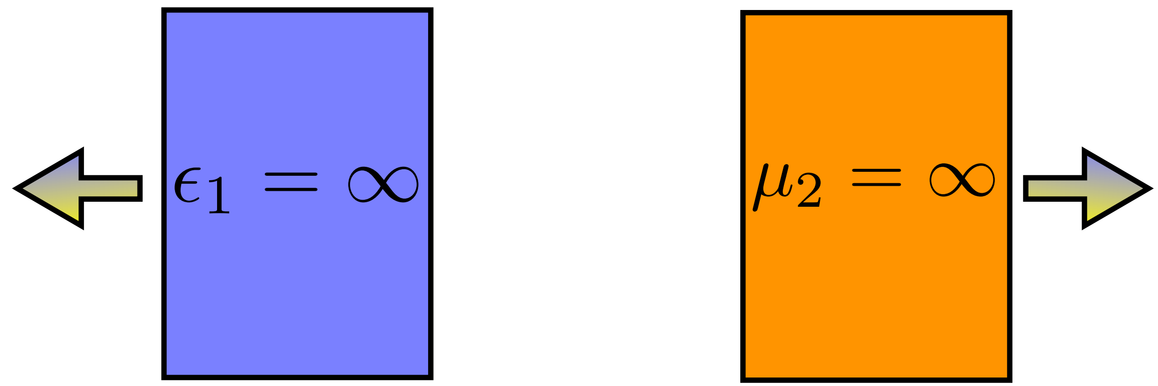


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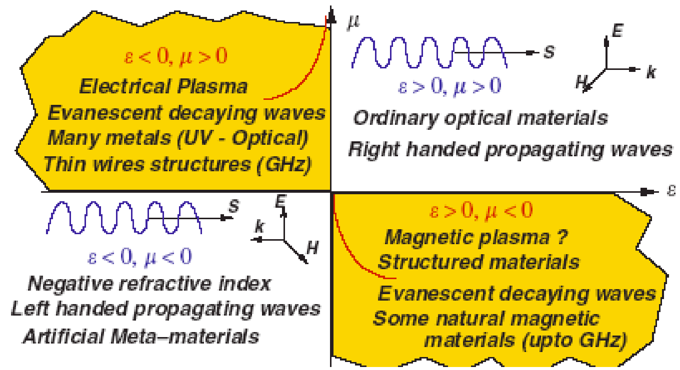
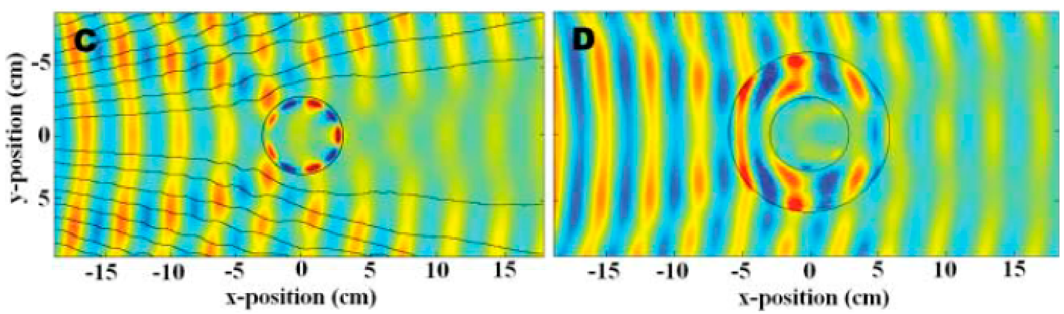
$\longrightarrow$ Metamaterials

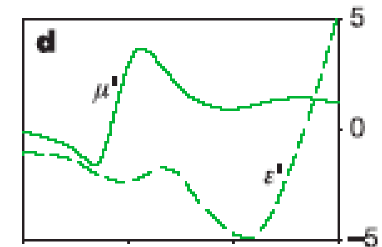
# Metamaterials

- Artificial structured composites with designer electromagnetic properties
- Macroscopic EM response described as dispersive magneto-dielectric media

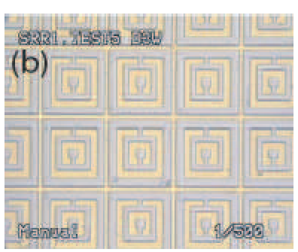
| | |
|---|---|
| Negative refraction | Veselago (1968), Smith et al (2000) |
| Perfect lens | Pendry (2000) |
| Cloaking | Smith et al (2007) |

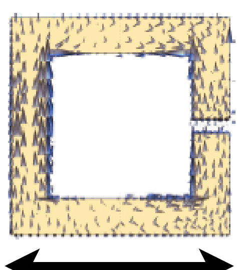


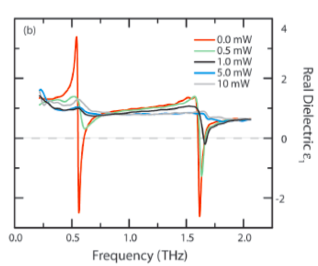




THz MMs: eg split ring resonators



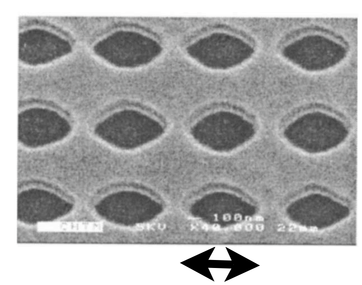


$36\mu m$

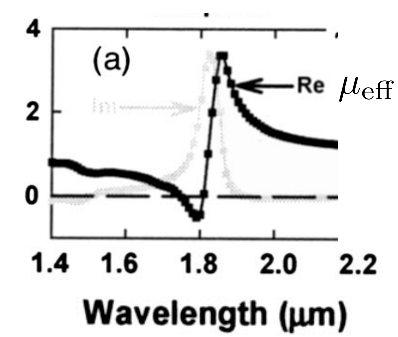



$\epsilon, \mu < 0$

Optical MMs: eg fishnets



400 nm



# Quantum levitation with MMs?





## Physicists have 'solved' mystery of levitation

**By Roger Highfield, Science Editor**
Last Updated: 1:41am BST 08/08/2007

Levitation has been elevated from being pure science fiction to science fact, according to a study reported today by physicists.

In earlier work the same team of theoretical physicists showed that invisibility cloaks are feasible.

Now, in another report that sounds like it comes out of the pages of a Harry Potter book, the University of St Andrews team has created an 'incredible levitation effects' by engineering the force of nature which normally causes objects to stick together.

Professor Ulf Leonhardt and Dr Thomas Philbin, from the University of St Andrews in Scotland, have worked out a way of reversing this phenomenon, known as the Casimir force, so that it repels instead of attracts.

Their discovery could ultimately lead to frictionless micro-machines with moving parts that levitate But they say that, in principle at least, the same effect could be used to levitate bigger objects too, even a person.

In theory the discovery could be used to levitate a person



The Casimir force is a consequence of quantum mechanics, the theory that describes the world of atoms and subatomic particles that is not only the most successful theory of physics but also the most baffling.

The force is due to neither electrical charge or gravity, for example, but the fluctuations in all-pervasive energy fields in the intervening empty space between the objects and is one reason atoms stick together, also explaining a "dry glue" effect that enables a gecko to walk across a ceiling.

Now, using a special lens of a kind that has already been built, Prof Ulf Leonhardt and Dr Thomas Philbin report in the New Journal of Physics they can engineer the Casimir force to repel, rather than attact.

Because the Casimir force causes problems for nanotechnologists, who are trying to build electrical circuits and tiny mechanical devices on silicon chips, among other things, the team believes the feat could initially be used to stop tiny objects from sticking to each other.

Prof Leonhardt explained, "The Casimir force is the ultimate cause of friction in the nano-world, in particular in some microelectromechanical systems.

Such systems already play an important role - for example tiny mechanical devices which triggers a car airbag to inflate or those which power tiny 'lab on chip' devices used for drugs testing or chemical analysis.

Micro or nano machines could run smoother and with less or no friction at all if one can manipulate the force." Though it is possible to levitate objects as big as humans, scientists are a long way off developing the technology for such feats, said Dr Philbin.

The practicalities of designing the lens to do this are daunting but not impossible and levitation "could happen over quite a distance".

Prof Leonhardt leads one of four teams - three of them in Britain - to have put forward a theory in a peer-reviewed journal to achieve invisibility by making light waves flow around an object - just as a river flows undisturbed around a smooth rock.



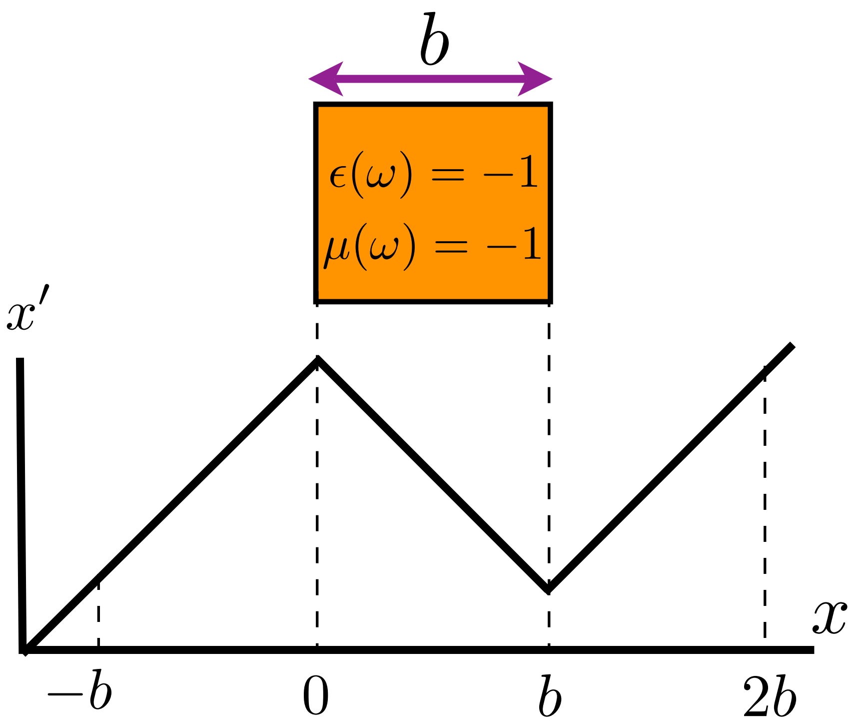


"In theory the discovery could be used to levitate a person"

# Quantum levitation with MMs?

## Transformation media

Leonhardt et al (2007)

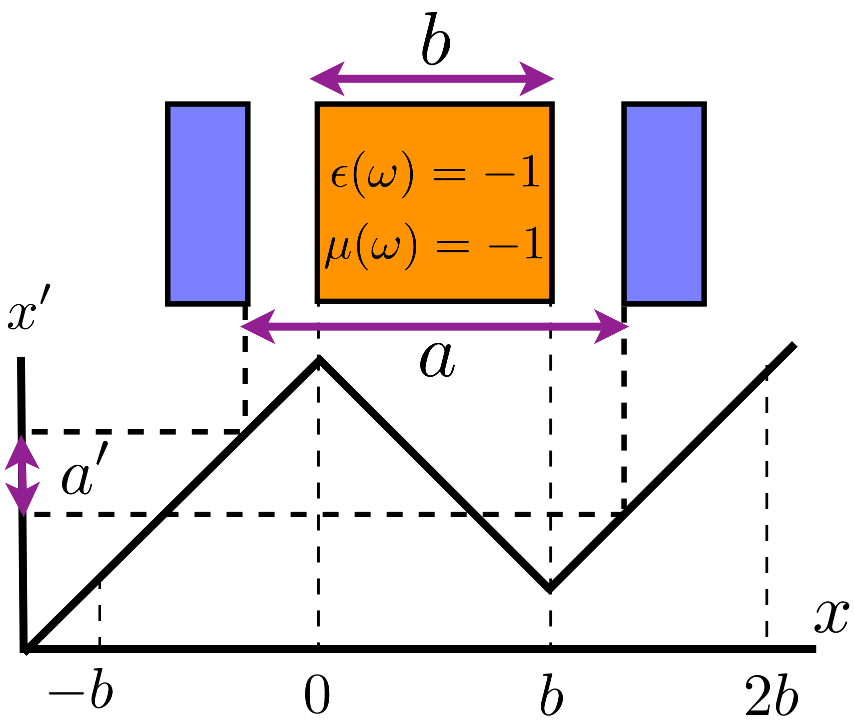



Perfect lens: EM field in -b<x<0 is mapped into x'. There are two images, one inside the device and one in b<x<2b.

# Quantum levitation with MMs?

## Transformation media

Leonhardt et al (2007)




**Perfect lens:** EM field in -b<x<0 is mapped into x'. There are two images, one inside the device and one in b<x<2b.

**Casimir cavity:** $a' = |a - 2b|$

When a< 2b (plates within the imaging range of the perfect lens)

$\Rightarrow$ $f = -\frac{\partial U}{\partial a'}\frac{\partial a'}{\partial a} = +\frac{\hbar c \pi^2}{240 a'^4}$ $\Rightarrow$ Repulsion

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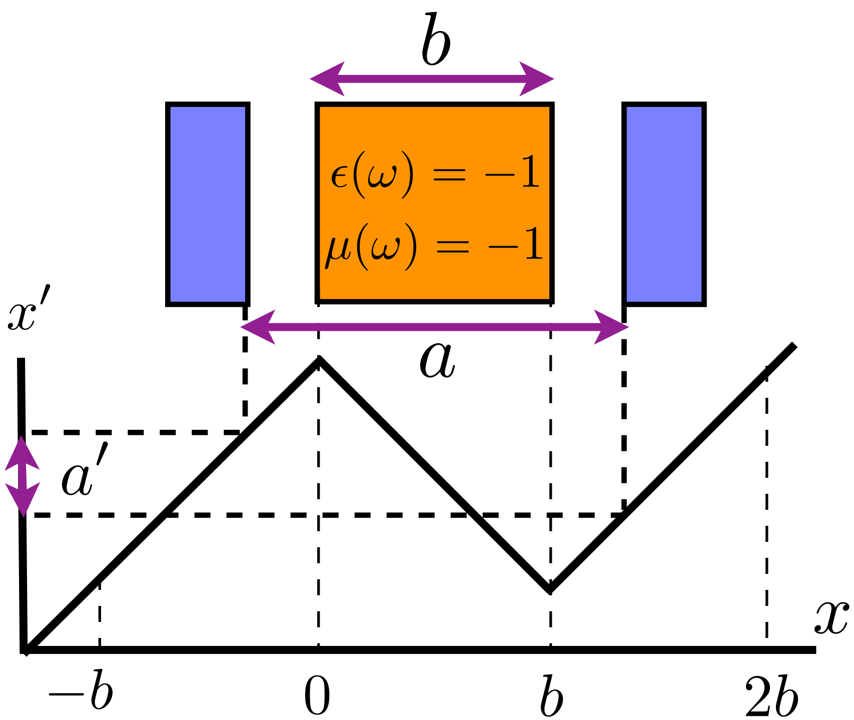


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$$\Rightarrow f = -\frac{\partial U}{\partial a'} \frac{\partial a'}{\partial a} = +\frac{\hbar c \pi^2}{240 a'^4} \Rightarrow \text{Repulsion}$$

For real materials, however .....

- According to causality, no passive medium ( $\epsilon"(\omega) > 0$ ) can sustain $\epsilon, \mu \simeq -1$ over a wide range of frequencies. In fact, $\epsilon(i\xi), \mu(i\xi) > 0$
- Another proposal is to use an active MM ( $\epsilon"(\omega) < 0$) in order to get repulsion. But then the whole approach breaks down, as real photons would be emitted into the quantum vacuum.

# Metamaterials for Casimir

## Drude-Lorentz model:

$$\boxed{\begin{aligned}\epsilon_\alpha(\omega) &= 1 - \frac{\Omega_{E,\alpha}^2}{\omega^2 - \omega_{E,\alpha}^2 + i\Gamma_{E,\alpha}\omega} \\ \mu_\alpha(\omega) &= 1 - \frac{\Omega_{M,\alpha}^2}{\omega^2 - \omega_{M,\alpha}^2 + i\Gamma_{M,\alpha}\omega}\end{aligned}}$$

Typical separations

$$d = 200 - 1000 \text{ nm}$$

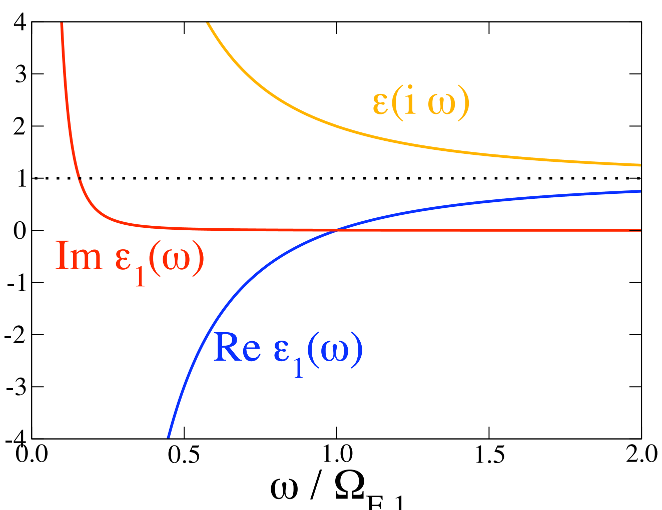
⇩

Infrared-optical frequencies

$$\Omega/2\pi = 5 \times 10^{14}\text{Hz}$$

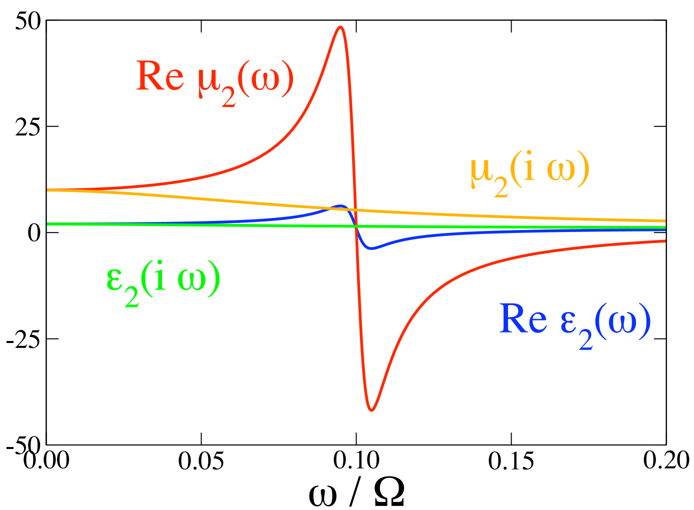
**Drude metal (Au)**

$\Omega_E = 9.0$ eV $\quad \Gamma_E = 35$ meV




**Metamaterial**

Re $\epsilon_2(\omega) < 0 \quad$ Re $\mu_2(\omega) < 0$




$$\Omega_{E,2}/\Omega = 0.1 \quad \Omega_{M,2}/\Omega = 0.3$$

$$\omega_{E,2}/\Omega = \omega_{M,2}/\Omega = 0.1$$

$$\Gamma_{E,2}/\Omega = \Gamma_{M,2}/\Omega = 0.01$$

# Metamaterials for Casimir

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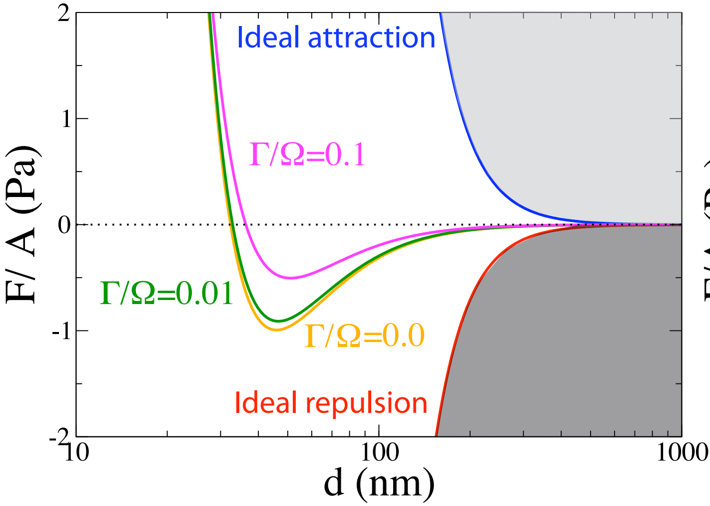
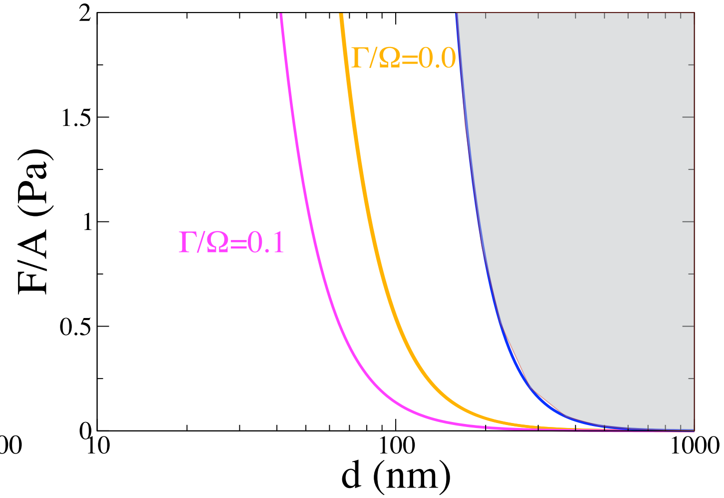
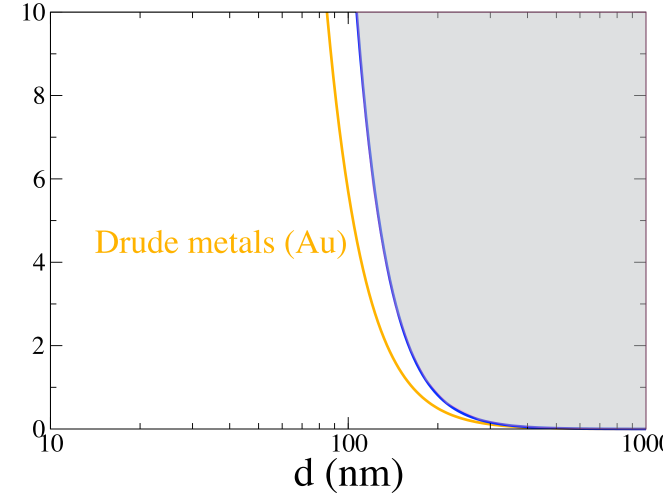
| Drude metal (Au) | Metamaterial | Drude metal (Au) |
|---|---|---|
| Metamaterial | Metamaterial | Drude metal (Au) |




| Repulsion-attraction | Only attraction | Only attraction |
|---|---|---|

A slab made of Au ($\rho = 19.3\ \mathrm{gr/cm^3}$) of width $\delta = 1\mu\mathrm{m}$ could levitate in front of one of these MMs at a distance of $d \approx 110\ \mathrm{nm}$ !!!

Casimir and metamaterials, Henkel et al (2005)

Casimir and surface plasmons, Intravaia et al (2005)

van der Waals in magneto-dielectrics, Spagnolo et al (2007)

# Summary II

- Metamaterials can strongly influence the quantum vacuum, providing a route towards quantum levitation.

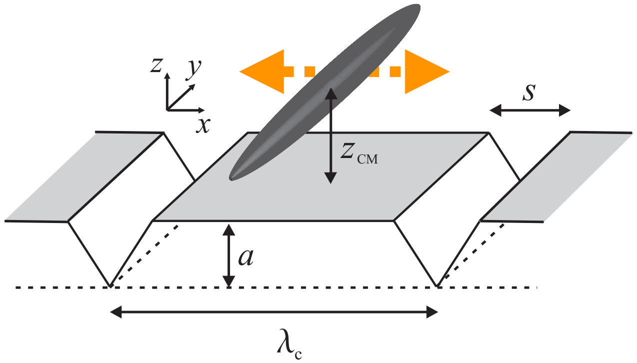
- Build MMs with strong magnetic response at infrared-optical frequencies, corresponding to gaps between 200 nm and 10 microns.

- Ongoing theoretical-experimental work at LANL to realize strongly modified / repulsive Casimir forces with metamaterials.

# General conclusions

## Casimir forces: still surprising after 60 years

☑ Non-trivial geometry effects

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